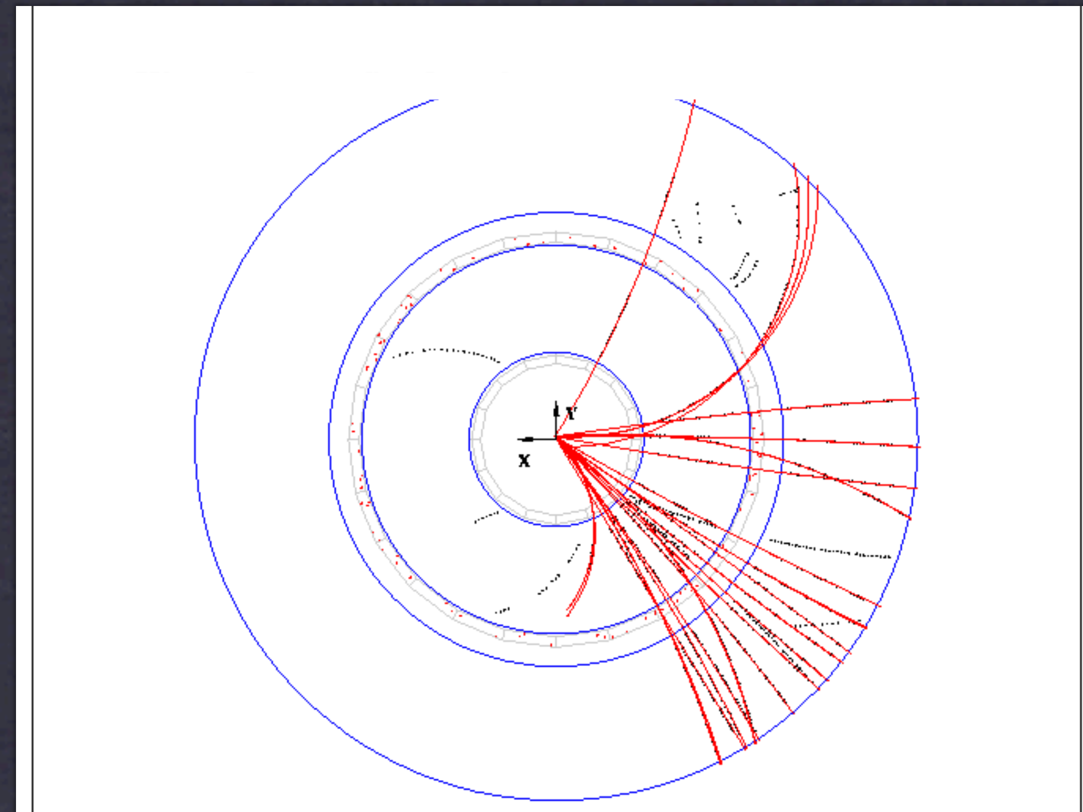
Queen Mary
University of London



NON-PERTURBATIVE

Particle Production from a HERA perspective

Daniel Traynor, Birmingham seminar

15/10/09

Overview

- The Trouble With QCD.
- HERA and the H1 experiment.
- Fragmentation functions.
- Strangeness production.
- Bonus : More strangeness, Instantons, Pentaquarks, Glueballs

The Trouble With QCD

QED

TO CUT A LONG STORY SHORT. THE INVARIANCE OF THE QED LAGRANGIAN UNDER LOCAL GAUGE TRANSFORMATIONS REQUIRES THE EXISTENCE OF A GAUGE FIELD. THIS IS THE ELECTROMAGNETIC FIELD AND MEDIATES THE FORCE BETWEEN CHARGED PARTICLES THE QUANTA OF THIS FIELD ARE THE MASSLESS PHOTONS

FIELD STRENGTH TENSOR

$$F_{\mu\nu} = \delta_\mu A_\nu - \delta_\nu A_\mu$$

U(1) SYMMETRY

ABELIAN

VECTOR FIELD Aμ (GAUGE FIELD) WHICH COUPLES TO CHARGE. IT IS A NUMBER

SYMBOLICALLY THE QED LAGRANGIAN HAS THESE TERMS

PROPAGATION OF CHARGED PARTICLES

PROPAGATION OF PHOTONS

INTERACTION OF PHOTONS AND CHARGED PARTICLES

The Trouble With QCD

QCD
TO CUT A LONG STORY SHORT. THE INVARIANCE OF THE QCD LAGRANGIAN UNDER LOCAL GAUGE TRANSFORMATIONS REQUIRES THE EXISTENCE OF A GAUGE FIELD. THIS IS THE COLOUR FIELD AND MEDIATES THE FORCE BETWEEN COLOURED PARTICLES. THE QUANTA OF THIS FIELD ARE THE MASSLESS GLUONS

FIELD STRENGTH TENSOR

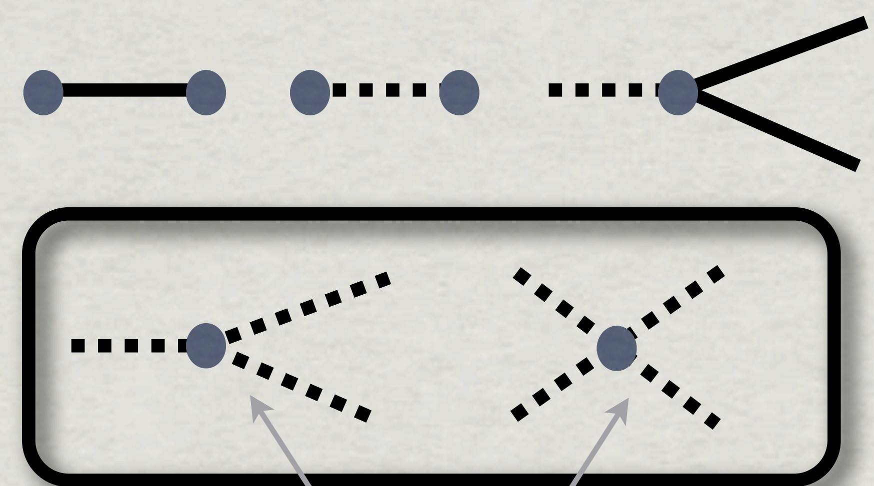
$$F_{\mu\nu} = \delta_\mu A_\nu - \delta_\nu A_\mu - ig[A_\mu A_\nu - A_\nu A_\mu]$$

SELF INTERACTION TERM

SU(3) SYMMETRY

NON-ABELIAN

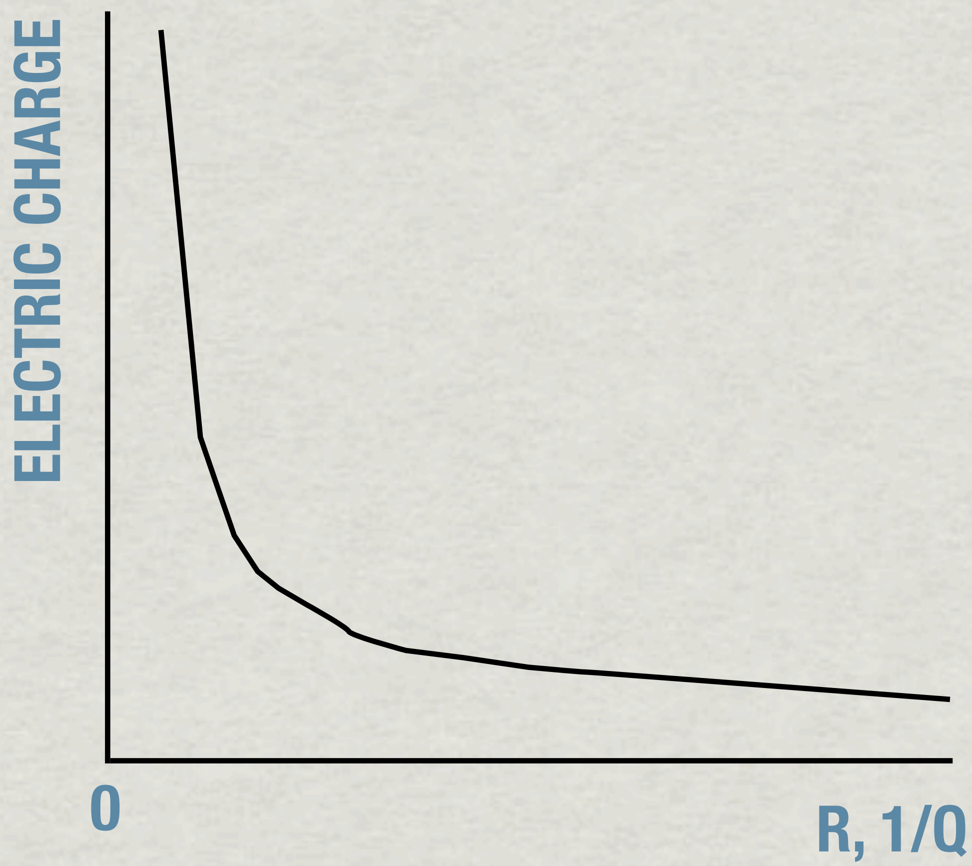
SYMBOLICALLY THE QCD LAGRANGIAN HAS THESE TERMS



THREE AND FOUR GLUON VERTICES

VECTOR FIELD Aμ (GAUGE FIELD) WHICH COUPLES TO COLOUR. IT IS A MATRIX

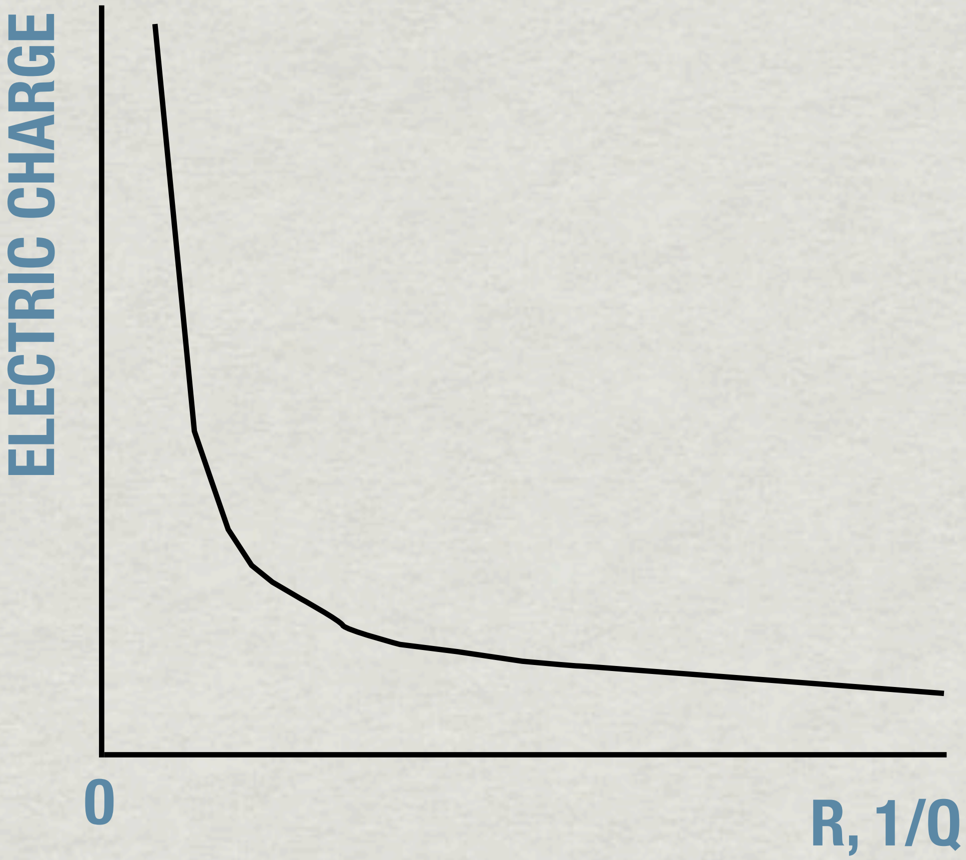
The Trouble With QCD



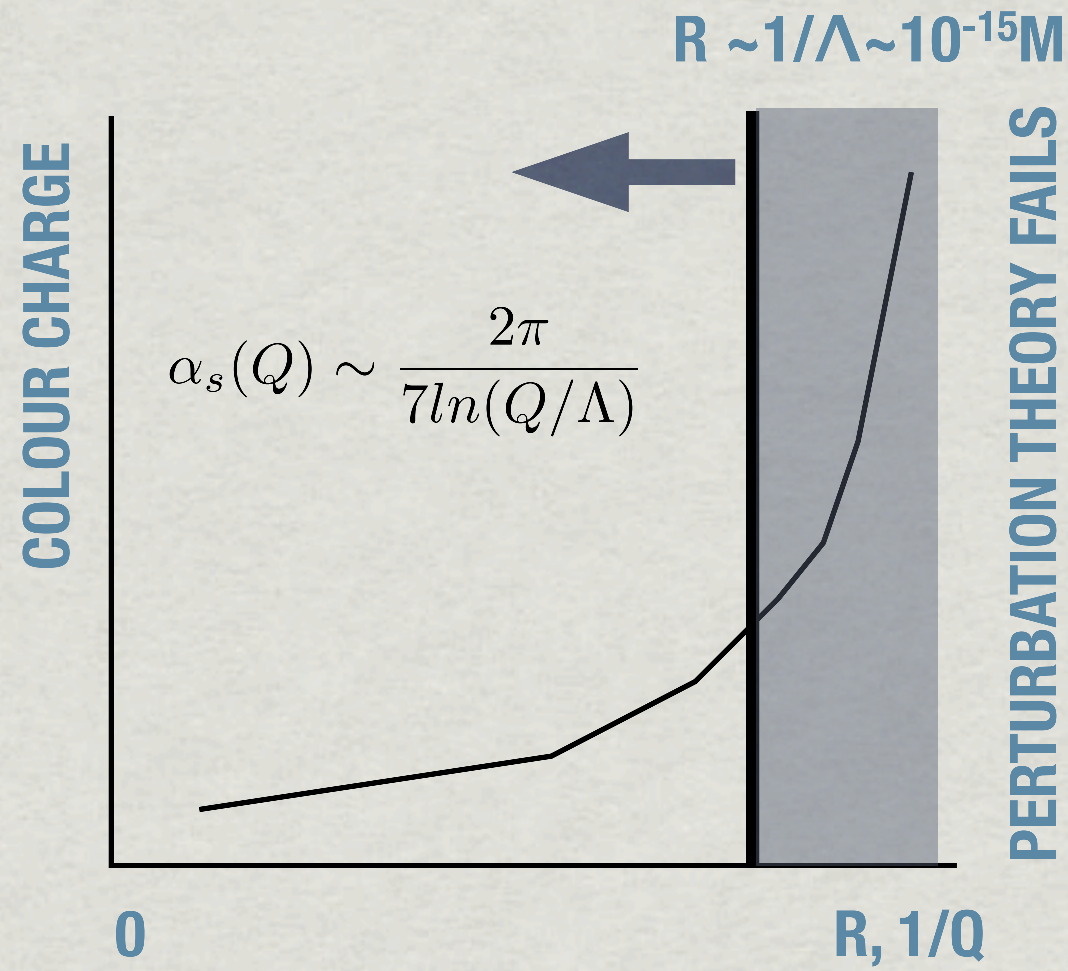
SCREENING OF ELECTRIC CHARGE

IN QED HIGHER ORDER PROCESSES ARE LESS IMPORTANT DUE TO THE SMALLNESS OF α_{em} (1/137).

The Trouble With QCD



SCREENING OF ELECTRIC CHARGE



ANTI SCREENING OF COLOUR CHARGE

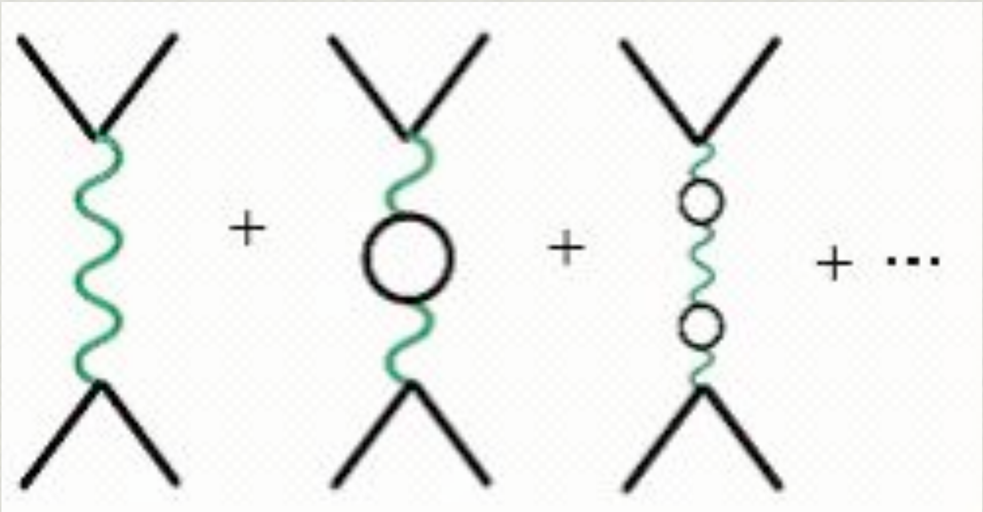
IN QED HIGHER ORDER PROCESSES ARE LESS IMPORTANT DUE TO THE SMALLNESS OF α_{em} (1/137).

AT LARGE DISTANCES α_s BECOMES LARGE (~1) AND HIGHER ORDER PROCESSES BECOME MORE IMPORTANT

ASYMPTOTIC FREEDOM AT SMALL DISTANCES

THE PERTURBATIVE EXPANSION

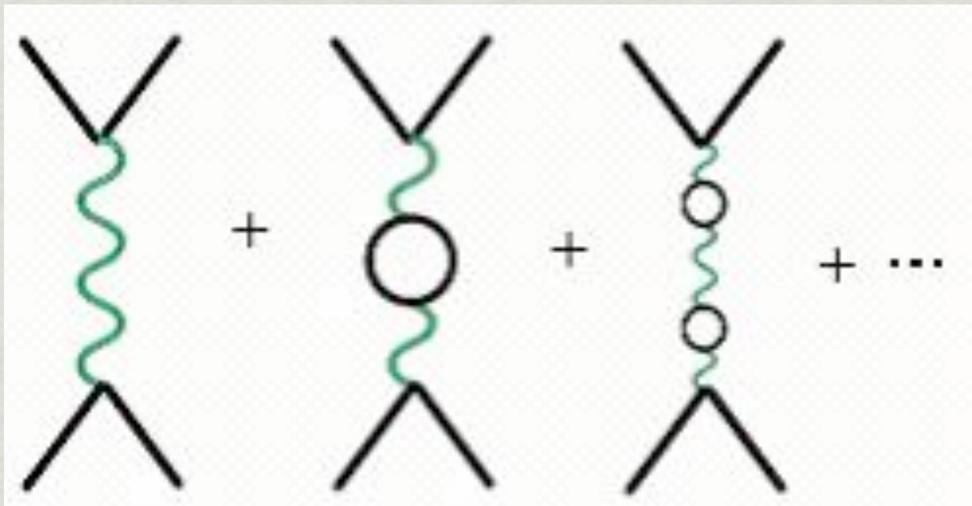
QED



α_{em} α^2_{em} α^3_{em}

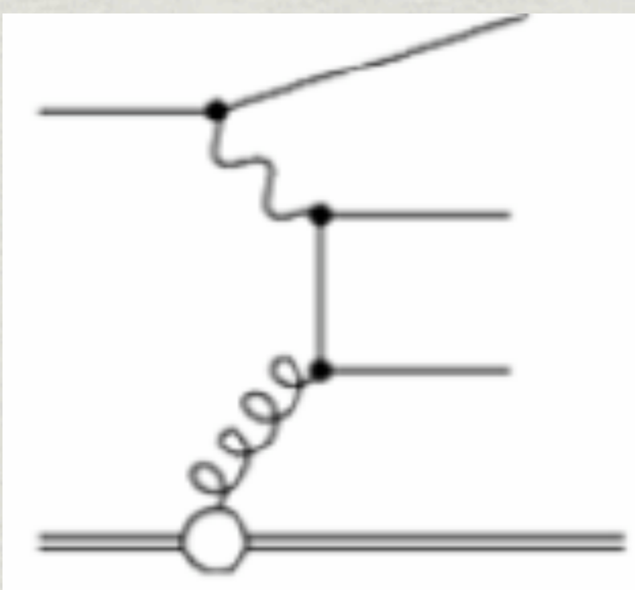
THE PERTURBATIVE EXPANSION

QED

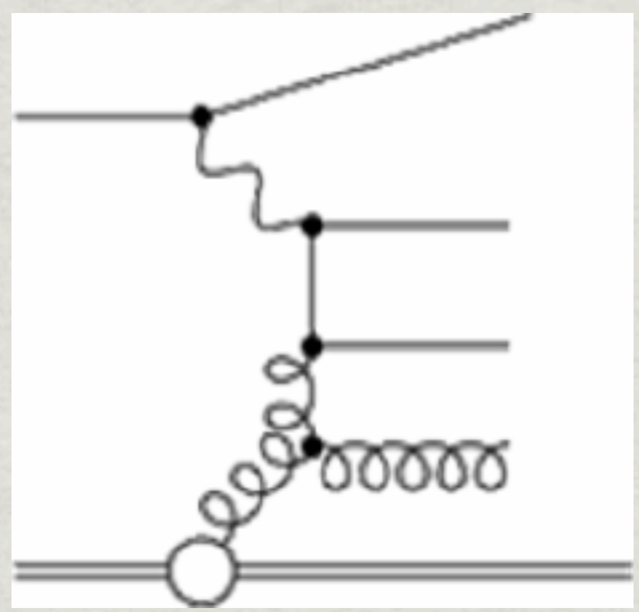


α_{em} α^2_{em} α^3_{em}

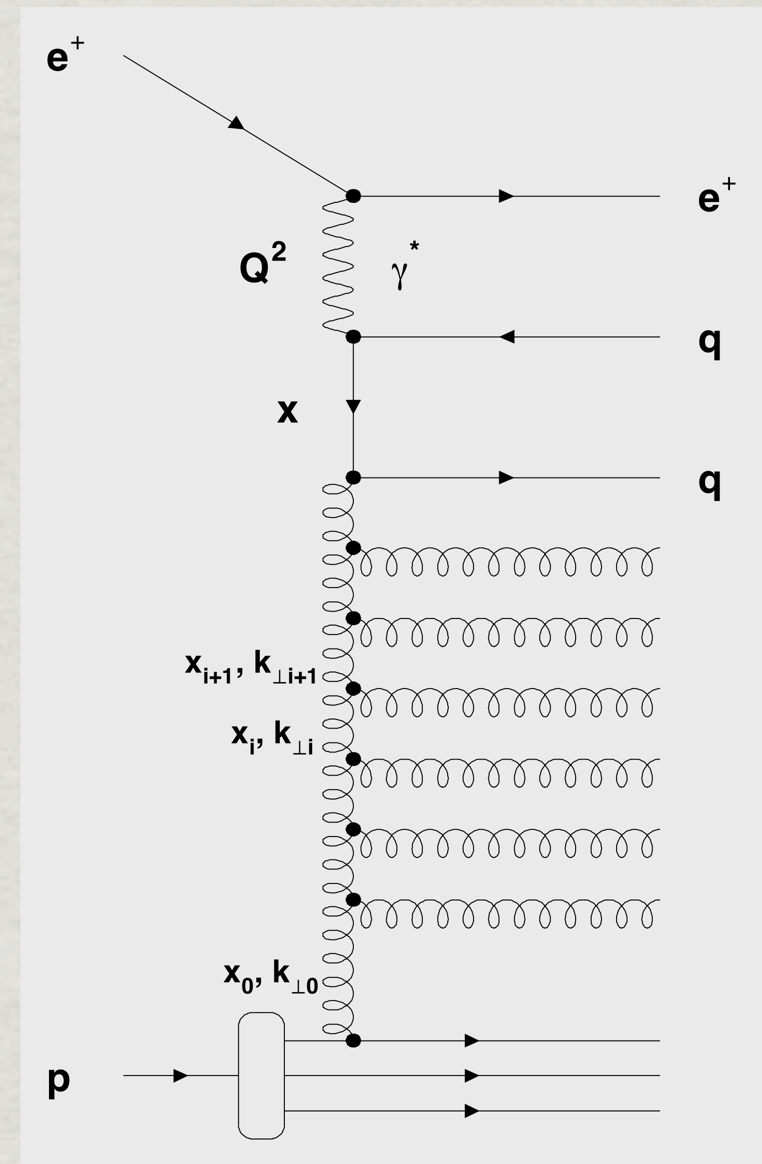
QCD



α_s



α^2_s



α^n_s

NLO time-like splitting functions (diagonal singlet)

α_s^2

$$\delta P^{(1)}_{\mathrm{ns},+}(x) \equiv P^{(1)T}_{\mathrm{ns},+}(x) - P^{(1)S}_{\mathrm{ns},+}(x) =$$
$$4{C_F}^2\Big(\mathrm{H}_0(6(1-x)^{-1}-5-x)+\mathrm{H}_{0,0}(-8(1-x)^{-1}+6+6x)+(\mathrm{H}_{1,0}+\mathrm{H}_2)(-8(1-x)^{-1}$$
$$+4+4x)\Big)\ .$$

q → q(g)

$$\delta P^{(1)}_{\mathrm{ps}}(x) \equiv P^{(1)T}_{\mathrm{ps}}(x) - P^{(1)S}_{\mathrm{ps}}(x) =$$
$$8C_F n_f\Big(-20/9\,x^{-1}-3-x+56/9\,x^2-(3+7x+8/3\,x^2)\,\mathrm{H}_0+2(1+x)\,\mathrm{H}_{0,0}\Big)\ .$$

g → qqg

$$\delta P^{(1)}_{\mathrm{gg}}(x) \equiv P^{(1)T}_{\mathrm{gg}}(x) - P^{(1)S}_{\mathrm{gg}}(x) =$$
$$8C_A^2\Big(p_{\mathrm{gg}}(x)\Big[11/3\,\mathrm{H}_0-4(\mathrm{H}_{0,0}+\mathrm{H}_{1,0}+\mathrm{H}_2)\Big]+[6(1-x)-22/3\,(x^{-1}-x^2)]\,\mathrm{H}_0$$
$$-8(1+x)\,\mathrm{H}_{0,0}\Big)\ -\ 16/3\,C_A n_f\,p_{\mathrm{gg}}(x)\,\mathrm{H}_0\ +\ 8C_F n_f\Big(20/9\,x^{-1}+3+x-56/9\,x^2$$
$$+[4+6x+4/3\,(x^{-1}+x^2)]\,\mathrm{H}_0+2(1+x)\,\mathrm{H}_{0,0}\Big)\ .$$

g → g(g)

...

NLO time-like splitting functions (diagonal singlet)

α_s^2

$$
\begin{aligned}
\delta P^{(1)}_{\mathrm{ns},+}(x) \;&\equiv\; P^{(1)T}_{\mathrm{ns},+}(x) - P^{(1)S}_{\mathrm{ns},+}(x) \;=\\
&4{C_F}^2\Big(\mathrm{H}_0(6(1-x)^{-1}-5-x)+\mathrm{H}_{0,0}(-8(1-x)^{-1}+6+6x)+(\mathrm{H}_{1,0}+\mathrm{H}_2)(-8(1-x)^{-1}\\
&+4+4x)\Big)\,.
\end{aligned}
$$

$$
\begin{aligned}
\delta P^{(1)}_{\mathrm{ps}}(x) \;&\equiv\; P^{(1)T}_{\mathrm{ps}}(x) - P^{(1)S}_{\mathrm{ps}}(x) \;=\\
&8C_Fn_f\Big(-20/9\,x^{-1}-3-x+56/9\,x^2-(3+7x+8/3\,x^2)\,\mathrm{H}_0+2(1+x)\,\mathrm{H}_{0,0}\Big)\,.
\end{aligned}
$$

$$
\begin{aligned}
\delta P^{(1)}_{\mathrm{gg}}(x) \;&\equiv\; P^{(1)T}_{\mathrm{gg}}(x) - P^{(1)S}_{\mathrm{gg}}(x) \;=\\
&8C_A^2\Big(p_{\mathrm{gg}}(x)\Big[11/3\,\mathrm{H}_0-4(\mathrm{H}_{0,0}+\mathrm{H}_{1,0}+\mathrm{H}_2)\Big]+[6(1-x)-22/3\,(x^{-1}-x^2)]\,\mathrm{H}_0\\
&-8(1+x)\,\mathrm{H}_{0,0}\Big)\;-\;16/3\,C_An_f\,p_{\mathrm{gg}}(x)\,\mathrm{H}_0\;+\;8C_Fn_f\Big(20/9\,x^{-1}+3+x-56/9\,x^2\\
&+[4+6x+4/3\,(x^{-1}+x^2)]\,\mathrm{H}_0+2(1+x)\,\mathrm{H}_{0,0}\Big)\,.
\end{aligned}
$$

$q \to q(g)$

$g \to q\bar{q}g$

$g \to g(g)$

...

NNLO time-like splitting functions (diagonal singlet)

α_s^3

$$
\begin{aligned}
\delta P^{(2)}_{\mathrm{ps},+}(x) \;&\equiv\; P^{(2)T}_{\mathrm{ps},+}(x) - P^{(2)S}_{\mathrm{ps},+}(x) \;=\\
&+16C_F^3\Big(p_{\mathrm{qq}}(x)\Big[311/24\,\mathrm{H}_0+4/3\,\mathrm{H}_0\zeta_2-169/9\,\mathrm{H}_{0,0}+8\mathrm{H}_{0,0}\zeta_2-22\mathrm{H}_{0,0,0}\\
&-268/9\,\mathrm{H}_{1,0}+8\mathrm{H}_{1,0}\zeta_2-44/3\,\mathrm{H}_{1,0,0}-268/9\,\mathrm{H}_2+8\mathrm{H}_2\zeta_2-44/3\,\mathrm{H}_{2,0}-44/3\,\mathrm{H}_3\Big]\\
&+(1+x)\Big[-4\mathrm{H}_{0,0}\zeta_2+25/2\,\mathrm{H}_{0,0,0}+\mathrm{H}_{2,0}+2\mathrm{H}_3\Big]-(1-x)\Big[325/18\,\mathrm{H}_0+50/3\,\mathrm{H}_{1,0}\\
&+50/3\,\mathrm{H}_2\Big]+(3-5x)\mathrm{H}_0\zeta_2-(173/18-691/18\,x)\mathrm{H}_{0,0}\Big)\\
&+16C_F^2\,(C_A-2C_F)\Big(p_{\mathrm{qq}}(x)\Big[151/24\,\mathrm{H}_0+\mathrm{H}_0\zeta_3+13/6\,\mathrm{H}_0\zeta_2-169/18\,\mathrm{H}_{0,0}+8\mathrm{H}_{0,0}\zeta_2\\
&-13/2\,\mathrm{H}_{0,0,0}-8\mathrm{H}_{0,0,0,0}-134/9\,\mathrm{H}_{1,0}+4\mathrm{H}_{1,0}\zeta_2-22/3\,\mathrm{H}_{1,0,0}-6\mathrm{H}_{1,0,0,0}-134/9\,\mathrm{H}_2\\
&+4\mathrm{H}_2\zeta_2-22/3\,\mathrm{H}_{2,0}-2\mathrm{H}_{2,0,0}-22/3\,\mathrm{H}_3-2\mathrm{H}_{3,0}-6\mathrm{H}_4\Big]+p_{\mathrm{qq}}(-x)\Big[-8\mathrm{H}_{-3,0}\\
&+8\mathrm{H}_{-2}\zeta_2+8\mathrm{H}_{-2,-1,0}+3\mathrm{H}_{-2,0}-14\mathrm{H}_{-2,0,0}-4\mathrm{H}_{-2,2}+8\mathrm{H}_{-1,-2,0}+16\mathrm{H}_{-1,-1,0,0}\\
&+8\mathrm{H}_{-1,0}\zeta_2+6\mathrm{H}_{-1,0,0}-18\mathrm{H}_{-1,0,0,0}-4\mathrm{H}_{-1,2,0}-8\mathrm{H}_{-1,3}-7\mathrm{H}_0\zeta_3+3/2\,\mathrm{H}_0\zeta_2\\
&-8\mathrm{H}_{0,0}\zeta_2-9/2\,\mathrm{H}_{0,0,0}+8\mathrm{H}_{0,0,0,0}+2\mathrm{H}_{3,0}+6\mathrm{H}_4\Big]-(1+x)\Big[4\mathrm{H}_{-2,0}+8\mathrm{H}_{-1,0,0}\Big]\\
&+(1-x)\Big[4\mathrm{H}_{-3,0}+4\mathrm{H}_{-2,0,0}-88/9\,\mathrm{H}_0+3\mathrm{H}_0\zeta_3-28/3\,\mathrm{H}_{1,0}-28/3\,\mathrm{H}_2\Big]-4x\mathrm{H}_0\zeta_2\\
&-(50/9-184/9\,x)\mathrm{H}_{0,0}-4x\mathrm{H}_{0,0}\zeta_2+(11/2+35/2\,x)\mathrm{H}_{0,0,0}+8x\mathrm{H}_{0,0,0,0}\Big)\\
&+16C_F^2\,n_f\Big(p_{\mathrm{qq}}(x)\Big[-11/12\,\mathrm{H}_0-2/3\mathrm{H}_0\zeta_2+11/9\,\mathrm{H}_{0,0}+2\mathrm{H}_{0,0,0}+20/9\,\mathrm{H}_{1,0}\\
&+4/3\,\mathrm{H}_{1,0,0}+20/9\,\mathrm{H}_2+4/3\,\mathrm{H}_{2,0}+4/3\,\mathrm{H}_3\Big]-(1+x)\,\mathrm{H}_{0,0,0}+(1-x)\Big[13/9\,\mathrm{H}_0\\
&+4/3\,\mathrm{H}_{1,0}+4/3\,\mathrm{H}_2\Big]+(8/9-28/9\,x)\mathrm{H}_{0,0}\Big)\,.
\end{aligned}
$$

$$
\begin{aligned}
\delta P^{(2)}_{\mathrm{ps}}(x) \;&\equiv\; P^{(2)T}_{\mathrm{ps}}(x) - P^{(2)S}_{\mathrm{ps}}(x) \;=\\
&+8C_AC_Fn_f\Big(269/6\,x^{-1}+14+113/2\,x-346/3\,x^2+\zeta_2\,(172+167x+8x^2)/3\\
&-\zeta_3\,(12x^{-1}-13+65x-28x^2)-2(1+x)\Big[16\zeta_2^2+4\mathrm{H}_{-1,0,0}+9\mathrm{H}_{3,0}+4\mathrm{H}_{3,1}\\
&+10\zeta_2\mathrm{H}_2-12\mathrm{H}_{2,0,0}-2\mathrm{H}_{2,1,0}-6\mathrm{H}_{2,2}-\mathrm{H}_4\Big]+8/3\,(x^{-1}+x^2)\Big[4\mathrm{H}_{-1,0,0}+\zeta_2\mathrm{H}_0\Big]\\
&-2(1-x)\Big[8\,(\mathrm{H}_{-3,0}+\mathrm{H}_{-2,0,0})+5\zeta_2\mathrm{H}_1-9\zeta_2\mathrm{H}_0+25/12\,\mathrm{H}_{1,0}-6\mathrm{H}_{1,0,0}-\mathrm{H}_{1,1,0}\\
&-3\mathrm{H}_{1,2}+\mathrm{H}_{2,1}\Big]+8/3(x^{-1}-x^2)\Big[6\mathrm{H}_{1,0,0}+\mathrm{H}_{1,1,0}+3\mathrm{H}_{1,2}-5\zeta_2\mathrm{H}_1-\mathrm{H}_{2,0}-\mathrm{H}_{2,1}\Big]\\
&+2/3\,(4x^{-1}+27-63x+28x^2)\,\mathrm{H}_{-2,0}-2/3\,(20x^{-1}-27+9x+56x^2)\,\mathrm{H}_{-1,0}\\
&+(89/9\,x^{-1}+55+1021/6\,x+2297/18\,x^2-46\zeta_3-22x\zeta_3)\,\mathrm{H}_0-(8/9\,x^{-1}\\
&+293/6+370/3\,x+538/9\,x^2+2\zeta_2(1-7x))\,\mathrm{H}_{0,0}-32x\mathrm{H}_{0,0,0,0}+(5-16/3\,x^{-1}\\
&+85x)\,\mathrm{H}_{0,0,0}-1/6\,(115x^{-1}+362-292x-185x^2)\,\mathrm{H}_1-(6x^{-1}+48+59x\\
&+22x^2)\,\mathrm{H}_2-2\,(5+x-8/3\,x^2)\,\mathrm{H}_{2,0}+4\,(2/3\,x^{-1}+x+2x^2)\,\mathrm{H}_3\Big)\\
&+8C_F^2n_f\Big(-217/18-55/3\,x^{-1}+122/9\,x+101/6\,x^2+\zeta_3\,(16x^{-1}+36+24x)\\
&-\zeta_2\,(127+188x+128x^2)/3+2(1+x)\Big[16\zeta_2^2+17\zeta_3\mathrm{H}_0+8\zeta_2\,x\mathrm{H}_0-7\zeta_2\mathrm{H}_{0,0}\\
&+10\zeta_2\mathrm{H}_2+9\mathrm{H}_{2,0}-12\mathrm{H}_{2,0,0}-2\mathrm{H}_{2,1,0}-6\mathrm{H}_{2,2}+9\mathrm{H}_{3,0}+4\mathrm{H}_{3,1}-\mathrm{H}_4\Big]\\
&+2(1-x)\Big[5\zeta_2\mathrm{H}_1+2\mathrm{H}_{2,0}+139/12\,\mathrm{H}_{1,0}-6\mathrm{H}_{1,0,0}-\mathrm{H}_{1,1,0}-3\mathrm{H}_{1,2}+\mathrm{H}_{2,1}\Big]\\
&+8/3\,(x^{-1}-x^2)\Big[5\zeta_2\mathrm{H}_1+5/3\,\mathrm{H}_{1,0}-6\mathrm{H}_{1,0,0}-\mathrm{H}_{1,1,0}-3\mathrm{H}_{1,2}+2\mathrm{H}_{2,0}+\mathrm{H}_{2,1}\Big]\\
&-(527+2473x+811x^2+72\zeta_2)/18\,\mathrm{H}_0+(62+81/2\,x+208/9\,x^2)\,\mathrm{H}_{0,0}\\
&+(6+18x-8x^2)\,\mathrm{H}_{0,0,0}+(385/18\,x^{-1}+190/3-143/3\,x-667/18\,x^2)\,\mathrm{H}_1\\
&+(28/9\,x^{-1}+71+46x+248/9\,x^2)\,\mathrm{H}_2-4/3(4x^{-1}-6-3x+8x^2)\mathrm{H}_3\Big)\\
&+8C_Fn_f^2\Big(2/9\,(23x-2x^{-1}-20-x^2)+2(1+x)\Big[\zeta_3-\zeta_2\mathrm{H}_0-\mathrm{H}_1+\mathrm{H}_{2,0}+\mathrm{H}_3\\
&-\mathrm{H}_{0,0,0}\Big]-(1-x)(\mathrm{H}_1-\mathrm{H}_{1,0})+4/3\,(x^{-1}-x^2)\,\mathrm{H}_{1,0}+2/9\,(3+18x+10x^2)\,\mathrm{H}_0\\
&-(7+x-4x^2)/3\,\mathrm{H}_{0,0}-(20x^{-1}-56x^2)/9\,\mathrm{H}_1+(3+7x+8/3\,x^2)\,(\zeta_2-\mathrm{H}_2)\Big)\,.
\end{aligned}
$$

$$
\begin{aligned}
\delta P^{(2)}_{\mathrm{gg}}(x) \;&\equiv\; P^{(2)T}_{\mathrm{gg}}(x) - P^{(2)S}_{\mathrm{gg}}(x) \;=\\
&+16C_A^3\Big(p_{\mathrm{gg}}(x)\Big[(1025/54-11/3\,\zeta_2-2\zeta_3)\,\mathrm{H}_0-49/3\,\mathrm{H}_{0,0}-33\mathrm{H}_{0,0,0}+16\mathrm{H}_{0,0,0,0}\\
&-(268/9-8\zeta_2)\,(\mathrm{H}_{1,0}+\mathrm{H}_2)-44/3\,(\mathrm{H}_{1,0,0}+\mathrm{H}_{2,0}+\mathrm{H}_3)+12\mathrm{H}_{1,0,0,0}+4\mathrm{H}_{2,0,0}\\
&+4\mathrm{H}_{3,0}+12\mathrm{H}_4\Big]+p_{\mathrm{gg}}(-x)\Big[+16\mathrm{H}_{-3,0}-16\zeta_2\mathrm{H}_{-2}-16\mathrm{H}_{-2,-1,0}-22/3\,\mathrm{H}_{-2,0}\\
&+28\mathrm{H}_{-2,0,0}+8\mathrm{H}_{-2,2}-16\mathrm{H}_{-1,-2,0}-32\mathrm{H}_{-1,-1,0,0}-16\zeta_2\mathrm{H}_{-1,0}-44/3\,\mathrm{H}_{-1,0,0}\\
&+36\mathrm{H}_{-1,0,0,0}+8\mathrm{H}_{-1,2,0}+16\mathrm{H}_{-1,3}+(14\zeta_3-11/3\,\zeta_2)\,\mathrm{H}_0+16\zeta_2\,\mathrm{H}_{0,0}+11\mathrm{H}_{0,0,0}\\
&-16\mathrm{H}_{0,0,0,0}-4\mathrm{H}_{3,0}-12\mathrm{H}_4\Big]+(1+x)\Big[-24\mathrm{H}_{-2,0}-48\mathrm{H}_{-1,0,0}+14/3\,\mathrm{H}_{2,0}\\
&+28/3\,\mathrm{H}_3\Big]+(1-x)\Big[32\,(\mathrm{H}_{-3,0}+\mathrm{H}_{-2,0,0})-(881/36-24\zeta_3)\,\mathrm{H}_0-27(\mathrm{H}_{1,0}+\mathrm{H}_2)\Big]\\
&-44/3\,(x^{-1}+x^2)\Big[2\mathrm{H}_{-2,0}+4\mathrm{H}_{-1,0,0}-\mathrm{H}_{2,0}-2\mathrm{H}_3\Big]+(x^{-1}-x^2)\Big[+2261/54\,\mathrm{H}_0\\
&+134/9\,(\mathrm{H}_{1,0}+\mathrm{H}_2)\Big]-(44x^{-1}+86+14x+132x^2)/3\,\zeta_2\mathrm{H}_0+(536x^{-1}+425\\
&+515x+752x^2+288\zeta_2)/9\,\mathrm{H}_{0,0}+(88x^{-1}-10+8x+44x^2)\,\mathrm{H}_{0,0,0}+64x\mathrm{H}_{0,0,0,0}\Big)\\
&+16C_A^2n_f\Big(p_{\mathrm{gg}}(x)\Big[-(158/27-2/3\,\zeta_2)\,\mathrm{H}_0-4/9\,\mathrm{H}_{0,0}+6\mathrm{H}_{0,0,0}+40/9\,(\mathrm{H}_{1,0}+\mathrm{H}_2)\\
&+8/3\,(\mathrm{H}_{1,0,0}+\mathrm{H}_{2,0}+\mathrm{H}_3)\Big]+2/3\,p_{\mathrm{gg}}(-x)\Big[2\mathrm{H}_{-2,0}+4\mathrm{H}_{-1,0,0}+\zeta_2\mathrm{H}_0-3\mathrm{H}_{0,0,0}\Big]\\
&-\frac{4}{3}(1+x)\Big[\zeta_2\mathrm{H}_0-\mathrm{H}_{2,0}-2\mathrm{H}_3\Big]-(1-x)\Big[173/9\,\mathrm{H}_0+2\,(\mathrm{H}_{1,0}+\mathrm{H}_2)\Big]+(x^{-1}-x^2)\\
&\Big[913/54\,\mathrm{H}_0+26/9\,(\mathrm{H}_{1,0}+\mathrm{H}_2)\Big]+4/9\,(35x^{-1}+21+48x)\,\mathrm{H}_{0,0}+4\,(1+4x)\,\mathrm{H}_{0,0,0}\Big)\\
&+\frac{16}{27}C_An_f^2\Big(p_{\mathrm{gg}}(x)\Big[10\mathrm{H}_0+12\mathrm{H}_{0,0}\Big]+12(1+x)\,\mathrm{H}_{0,0}+(13\,(x^{-1}-x^2)-9+9x)\,\mathrm{H}_0\Big)\\
&+8C_AC_Fn_f\Big(-2p_{\mathrm{gg}}(x)\,\mathrm{H}_0-269/6\,x^{-1}-14-113/2\,x+346/3\,x^2-\zeta_2\,(172+167x\\
&+8x^2)/3+\zeta_3\,(12x^{-1}-13+65x-28x^2)+2(1+x)\Big[16\zeta_2^2+2\mathrm{H}_{-2,0}-4\mathrm{H}_{-1,0,0}\\
&+17\zeta_3\mathrm{H}_0+4/3\,\zeta_2\mathrm{H}_0-3\zeta_2\mathrm{H}_{0,0}+10\zeta_2\mathrm{H}_2-12\mathrm{H}_{2,0,0}-2\mathrm{H}_{2,1,0}-6\mathrm{H}_{2,2}+4\mathrm{H}_{3,1}\\
&+9\mathrm{H}_{3,0}-\mathrm{H}_4\Big]+8/3\,(x^{-1}+x^2)\Big[4\mathrm{H}_{-1,0,0}+\zeta_2\mathrm{H}_0\Big]-2(1-x)\Big[8(\mathrm{H}_{-3,0}+\mathrm{H}_{-2,0,0})\\
&+18\mathrm{H}_{-2,0}+9\zeta_2\mathrm{H}_0+6\zeta_3\mathrm{H}_0+4\zeta_2\mathrm{H}_{0,0}-145/12\,\mathrm{H}_{1,0}\Big]+\Big[\frac{8}{3}(x^{-1}-x^2)+2(1-x)\Big]\\
&\Big[3\mathrm{H}_{-2,0}-11/3\,\mathrm{H}_{1,0}+5\zeta_2\mathrm{H}_1-6\mathrm{H}_{1,0,0}-\mathrm{H}_{1,1,0}-3\mathrm{H}_{1,2}+\mathrm{H}_{2,1}\Big]+(40x^{-1}-54\\
&+18x+112x^2)/3\,\mathrm{H}_{-1,0}-(59x^{-1}+45+1081/6\,x+157/2\,x^2)\,\mathrm{H}_0-(464x^{-1}\\
&+329/2-146x-66x^2)/9\,\mathrm{H}_{0,0}-(80/3\,x^{-1}-17+15x)\,\mathrm{H}_{0,0,0}-32x\mathrm{H}_{0,0,0,0}\\
&+(115x^{-1}+362-292x-185x^2)/6\,\mathrm{H}_1-1/9\,(34x^{-1}-546-417x-286x^2)\,\mathrm{H}_2\\
&+(8x^{-1}+10-14x-24x^2)/3\,\mathrm{H}_{2,0}-8/3\,(x^{-1}+5+13/2\,x+3x^2)\,\mathrm{H}_3\Big)\\
&+8C_F^2n_f\Big(217/18+55/3\,x^{-1}-122/9\,x-101/6\,x^2-\zeta_3\,(16x^{-1}+36+24x)+\zeta_2/3\\
&(127+188x+128x^2)-2(1+x)\Big[16\zeta_2^2+\zeta_2\mathrm{H}_{0,0}+10\zeta_2\mathrm{H}_2+17\zeta_3\mathrm{H}_0-12\mathrm{H}_{2,0,0}\\
&-2\mathrm{H}_{2,1,0}-6\mathrm{H}_{2,2}+9\mathrm{H}_{3,0}+4\mathrm{H}_{3,1}-\mathrm{H}_4\Big]-\Big[\frac{8}{3}(x^{-1}-x^2)+2(1-x)\Big]\Big[5\zeta_2\mathrm{H}_1\\
&+3\mathrm{H}_{1,0}-6\mathrm{H}_{1,0,0}-3\mathrm{H}_{1,2}-\mathrm{H}_{1,1,0}+\mathrm{H}_{2,1}\Big]+(4x^{-1}+283/6+239/2\,x+739/18\,x^2\\
&-8\zeta_2-20\zeta_2x-16/3\,\zeta_2x^2)\,\mathrm{H}_0-(18+97/2\,x+16x^2)\,\mathrm{H}_{0,0}-(6-6x+8x^2)\,\mathrm{H}_{0,0,0}\\
&-(385x^{-1}+1140-858x-667x^2)/18\,\mathrm{H}_1+53/6\,(1-x)\mathrm{H}_{1,0}-(20/3\,x^{-1}+45\\
&+72x+24x^2)\,\mathrm{H}_2-(32/3\,x^{-1}+14+6x)\,\mathrm{H}_{2,0}-(16/3\,x^{-1}-8-12x)\,\mathrm{H}_3\Big)\\
&+8/9\,C_Fn_f^2\Big(4x^{-1}+40-46x+2x^2-9\zeta_2\,(3+7x+8/3\,x^2)-6(1+x)\Big[3\zeta_3+\zeta_2\mathrm{H}_0\\
&+3\mathrm{H}_{0,0,0}-\mathrm{H}_{2,0}-5\mathrm{H}_3\Big]-(92/3\,x^{-1}-6+48x-32/3\,x^2)\,\mathrm{H}_0-(16x^{-1}+83\\
&+101x+28x^2)\,\mathrm{H}_{0,0}+(20x^{-1}+27+9x-56x^2)\,\mathrm{H}_1+(4x^{-1}+3-3x-4x^2)\,\mathrm{H}_{1,0}\\
&+(16x^{-1}+39+51x+8x^2)\,\mathrm{H}_2\Big)\,.
\end{aligned}
$$

S.M., Vogt '07

2007

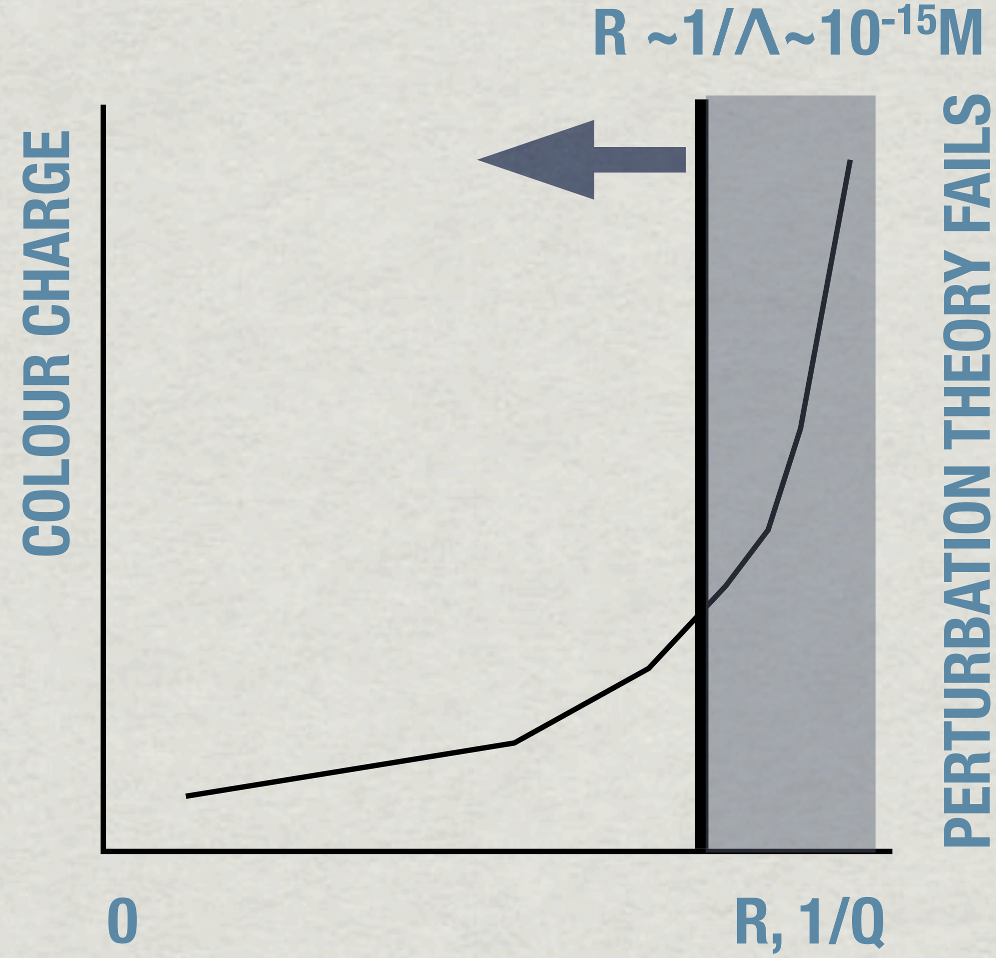
The Trouble With QCD

FACTORISATION

SPLIT THE THEORY INTO PARTS;
SHORT DISTANCES WHERE PREDICTIONS CAN BE MADE
LARGE DISTANCES WHERE APPROXIMATIONS HAVE TO BE MADE

QUARKS MUST FRAGMENT IN TO HADRONS WITH UNIT PROBABILITY

CONFINEMENT HAPPENS IN THE REGION WHERE PERTURBATION THEORY FAILS



WE HAVE TO USE MODELS OF WHAT WE THINK IS HAPPENING BUT BASED ON QCD. THESE MODELS CAN HAVE DIFFERENT ASSUMPTIONS AND A VERITY OF PARAMETERS.

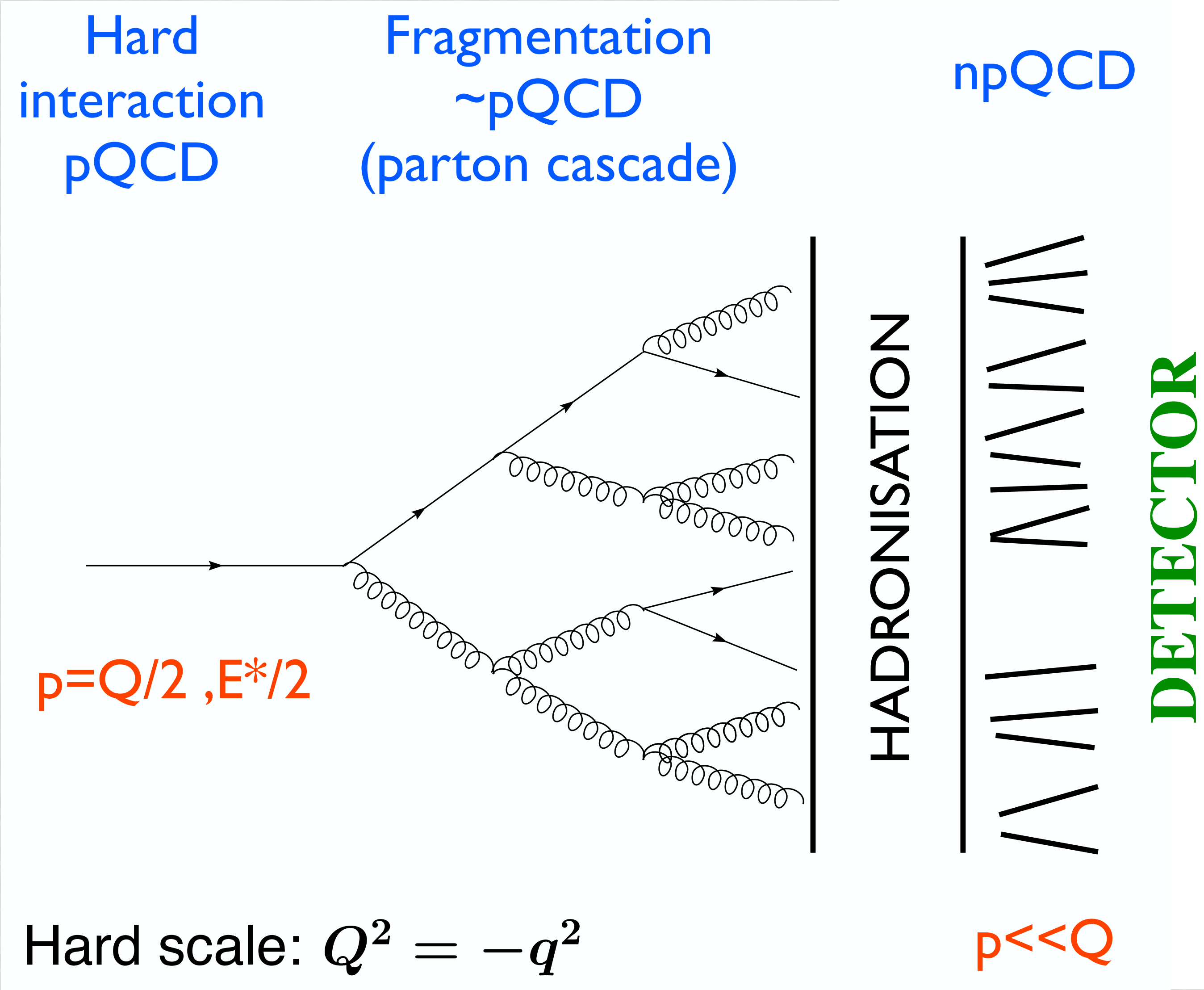
THESE ASSUMPTIONS AND PARAMETERS NEED TO BE CONFRONTED WITH AND TUNED TO DATA

Working QCD Model

STARTING SCALE GIVEN BY HARD SCALE Q

PROBABILITY OF PARTON EMISSION GIVEN BY THE "QCD" SPLITTING FUNCTIONS, REDUCING Q

AT SOME FIXED VALUE "Q_0" THE EVOLUTION IS STOPPED AND THE PARTONS ARE HADRONISED



LO , NLO ME

DGLAP, BFKL, CCFM, MLLA ETC..

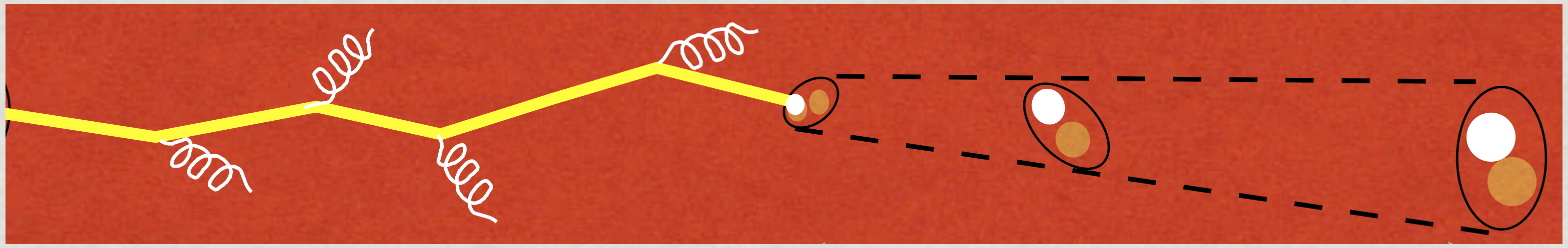
LPHD, STRING, CLUSTER

Universality of Fragmentation

VACUUM

COMPLEXITY

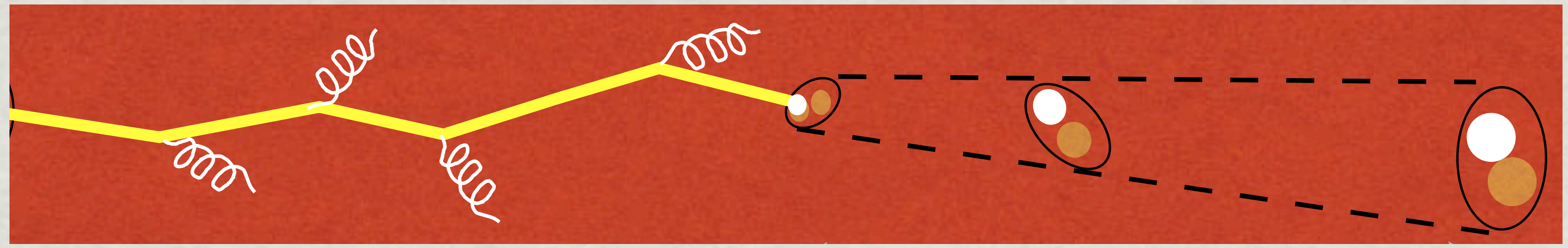
MEDIUM



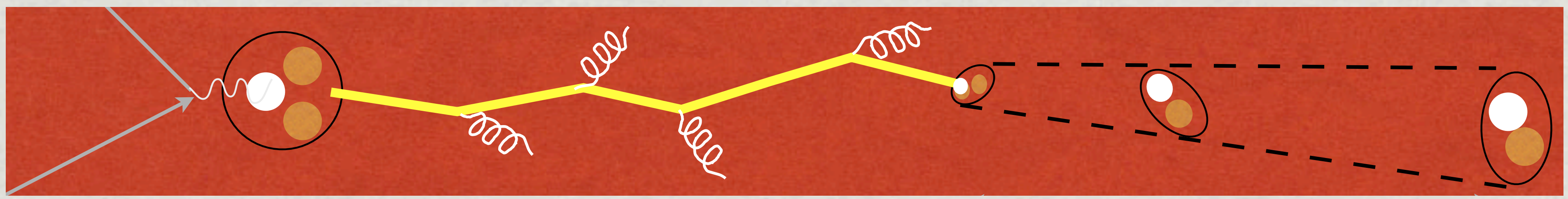
PETRA,
SLC,LEP

Universality of Fragmentation

VACUUM



PETRA,
SLC,LEP



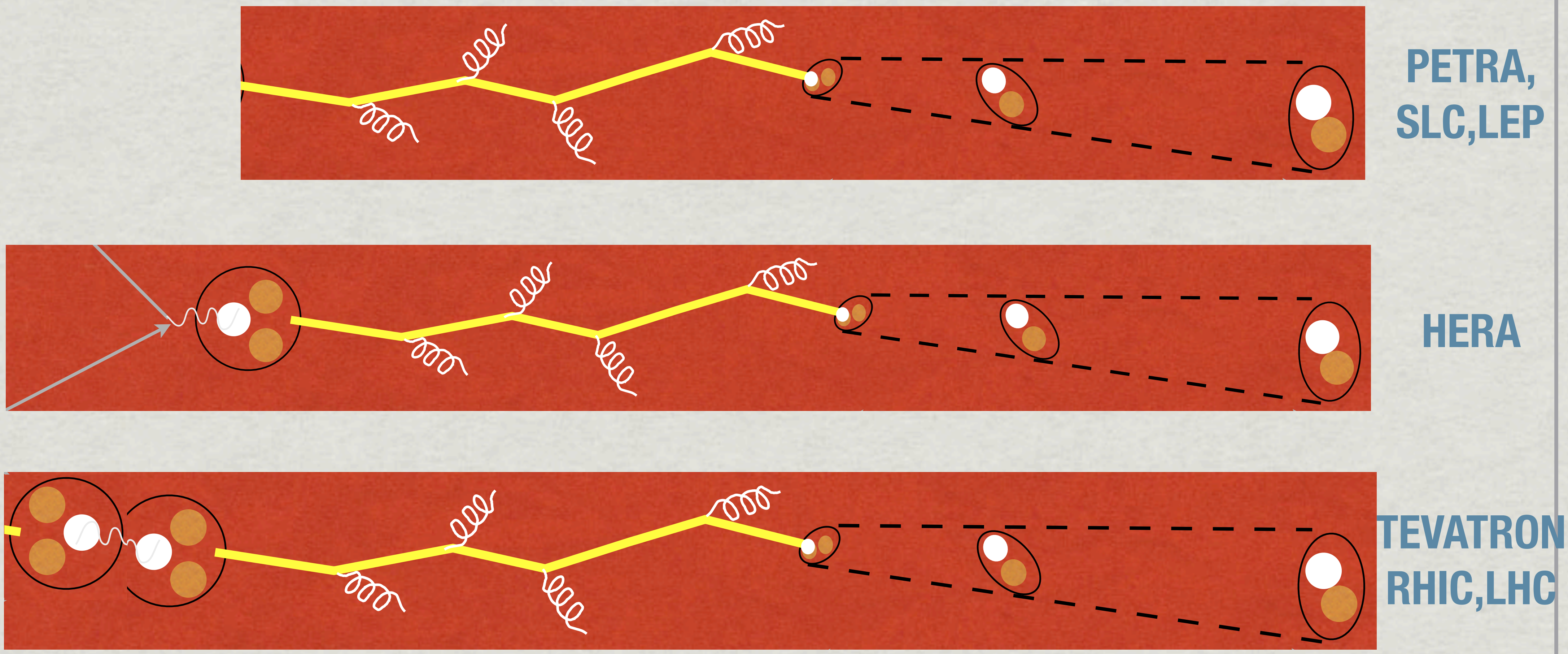
HERA

COMPLEXITY

MEDIUM

Universality of Fragmentation

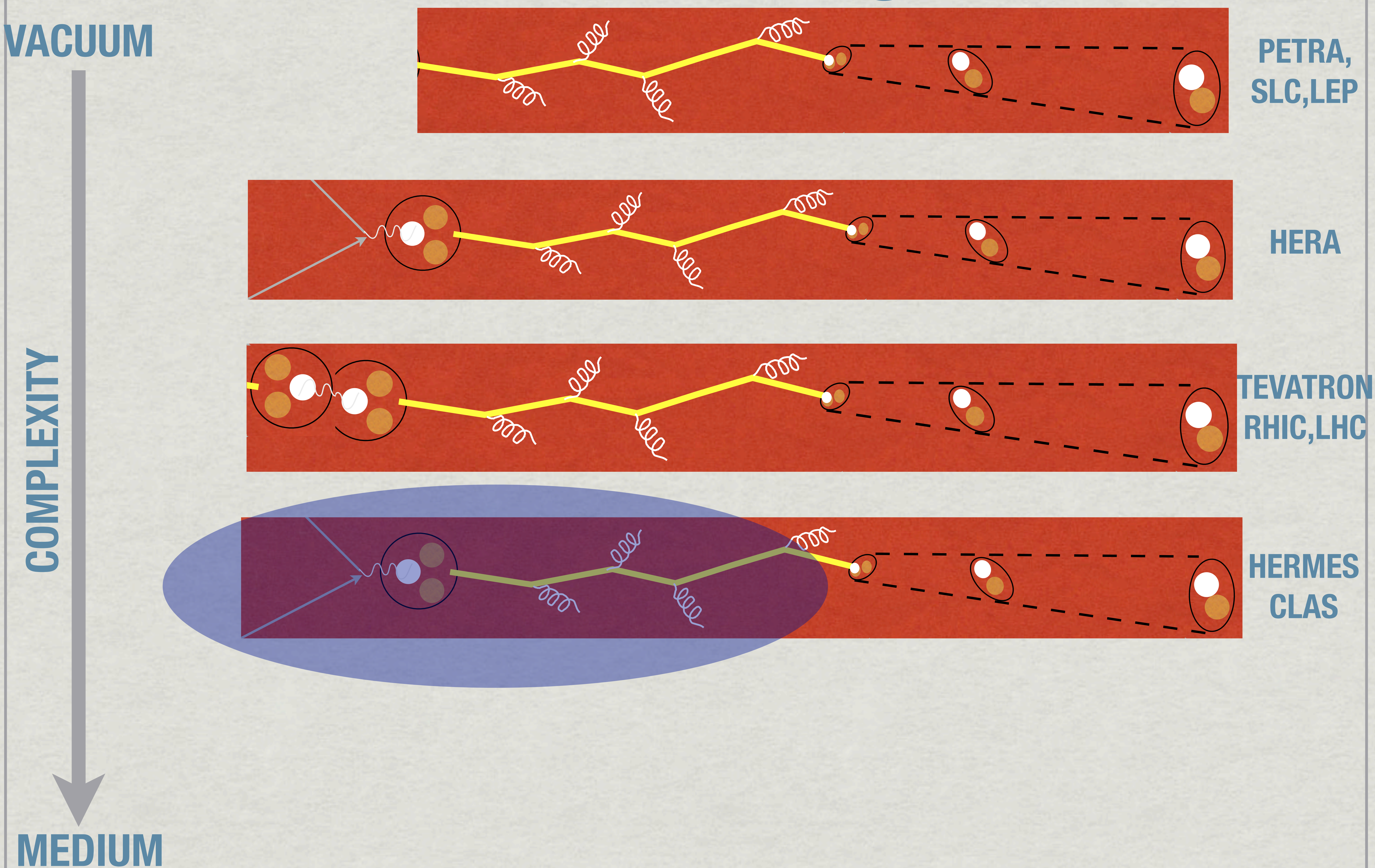
VACUUM



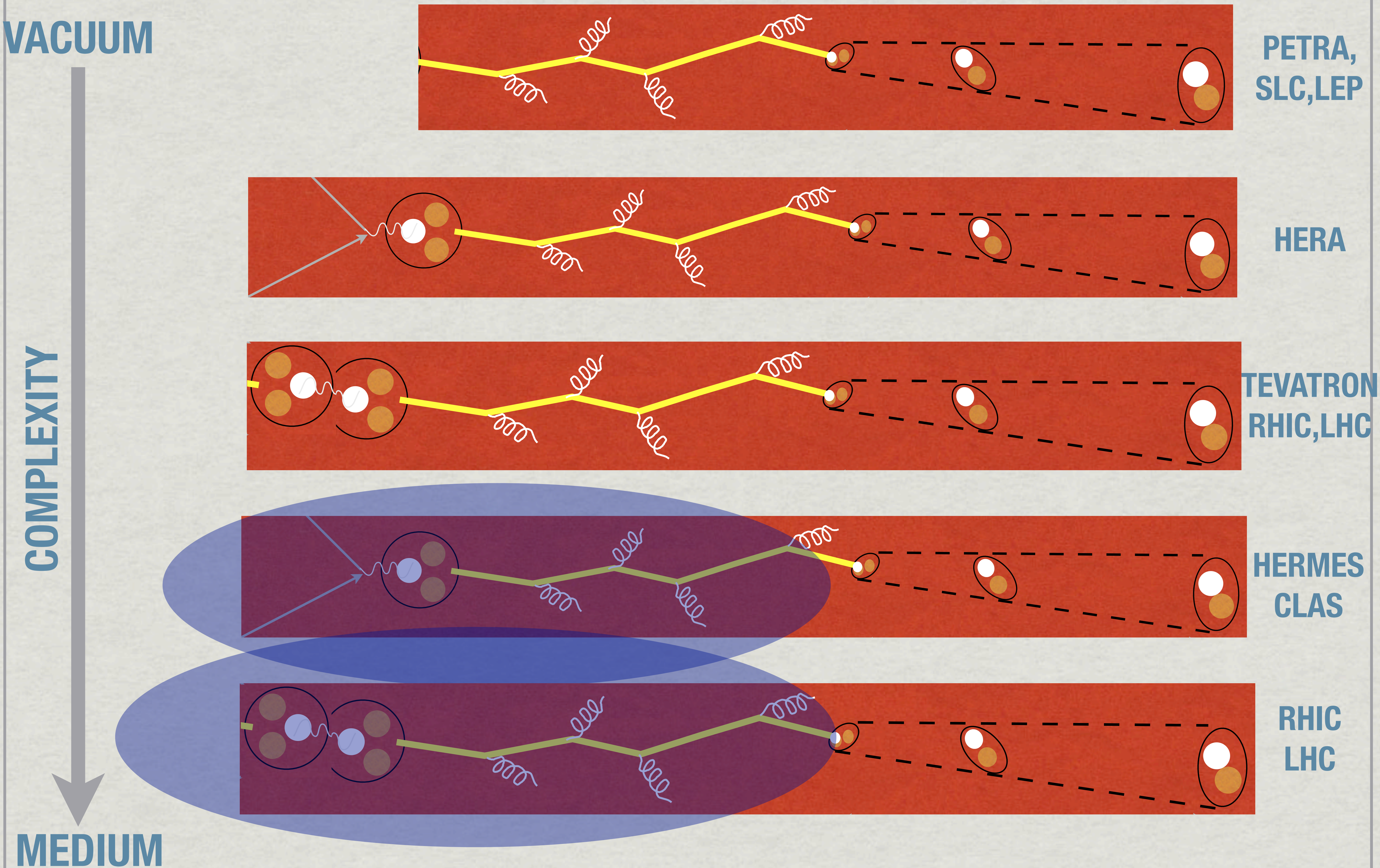
COMPLEXITY

MEDIUM

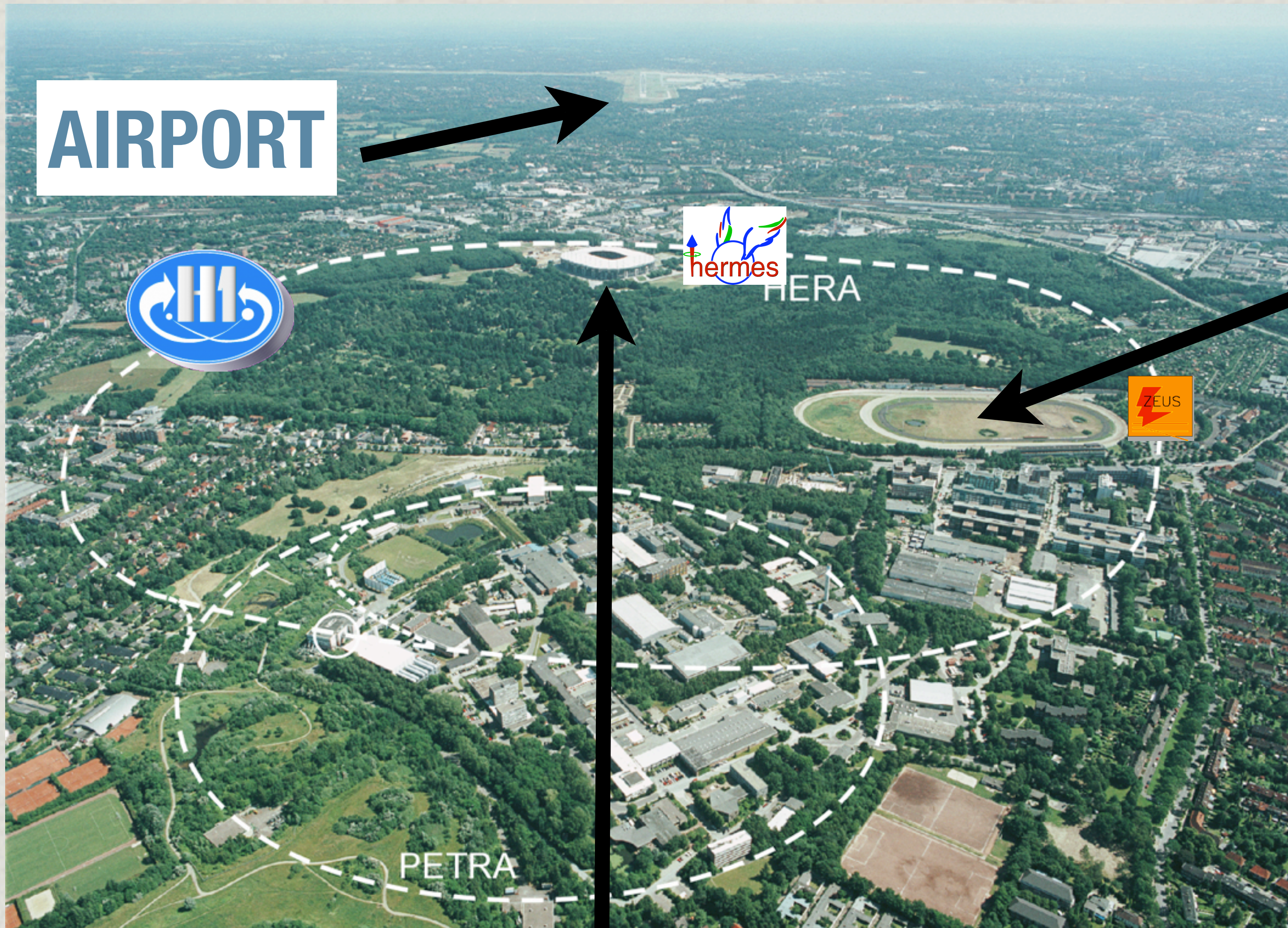
Universality of Fragmentation



Universality of Fragmentation



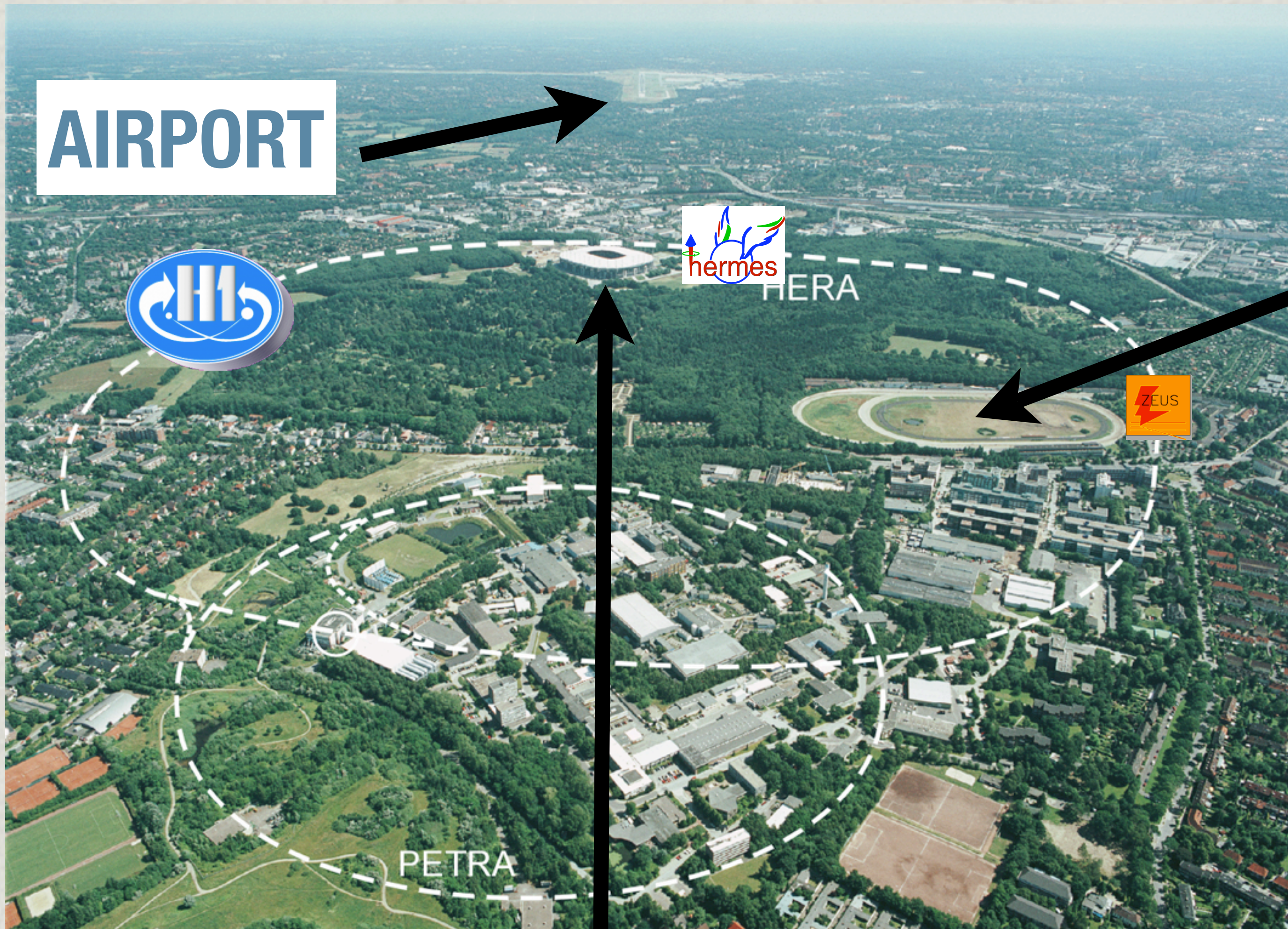
HERA & Hamburg



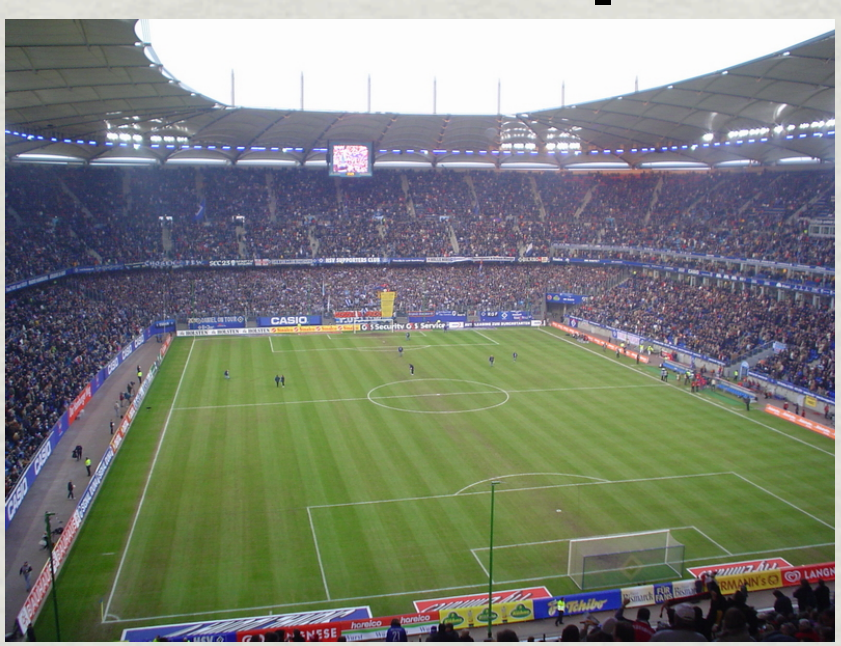
TRABRENNEN

HSV STADIUM

HERA & Hamburg

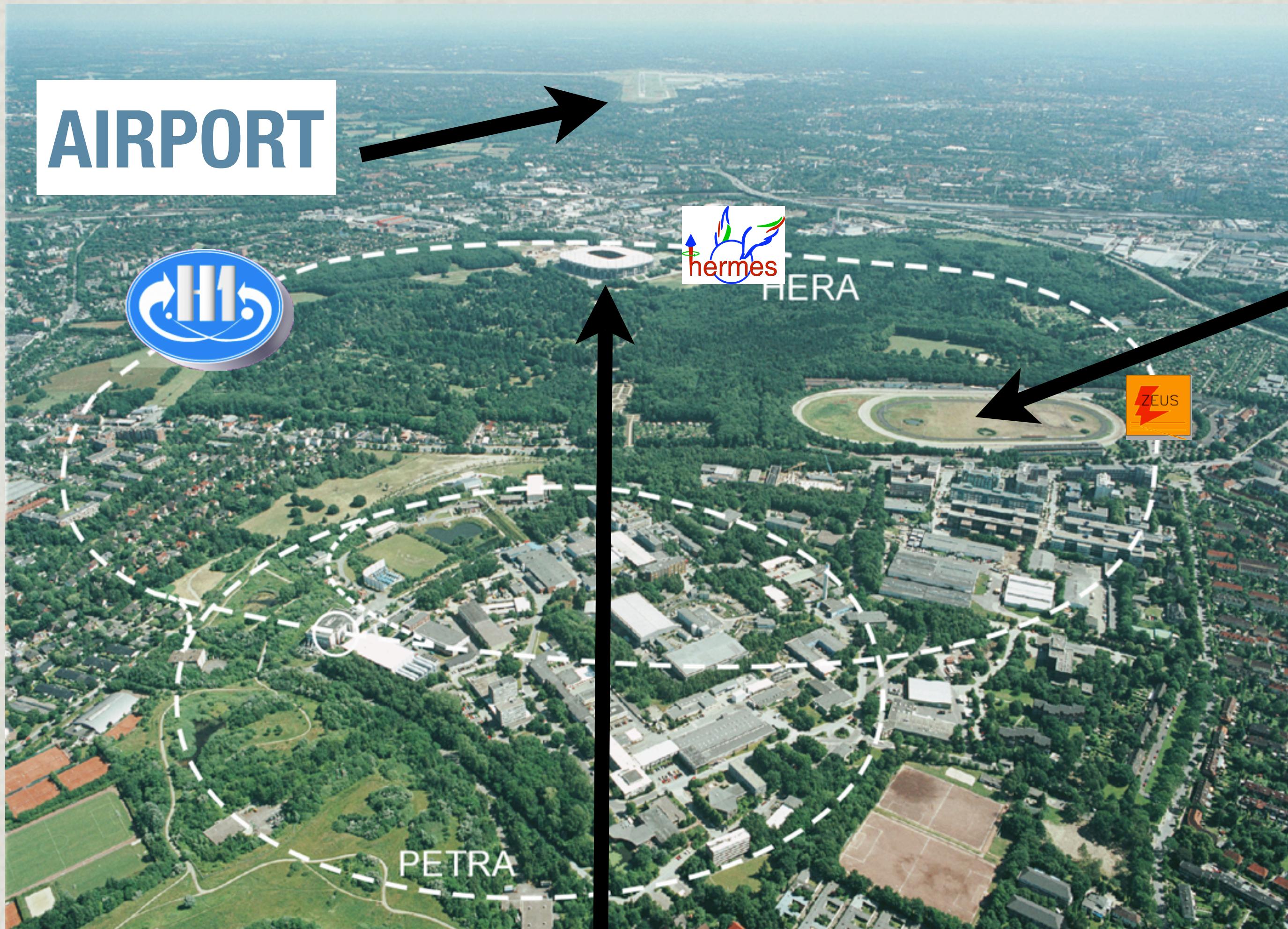


TRABRENNEN



HSV STADIUM

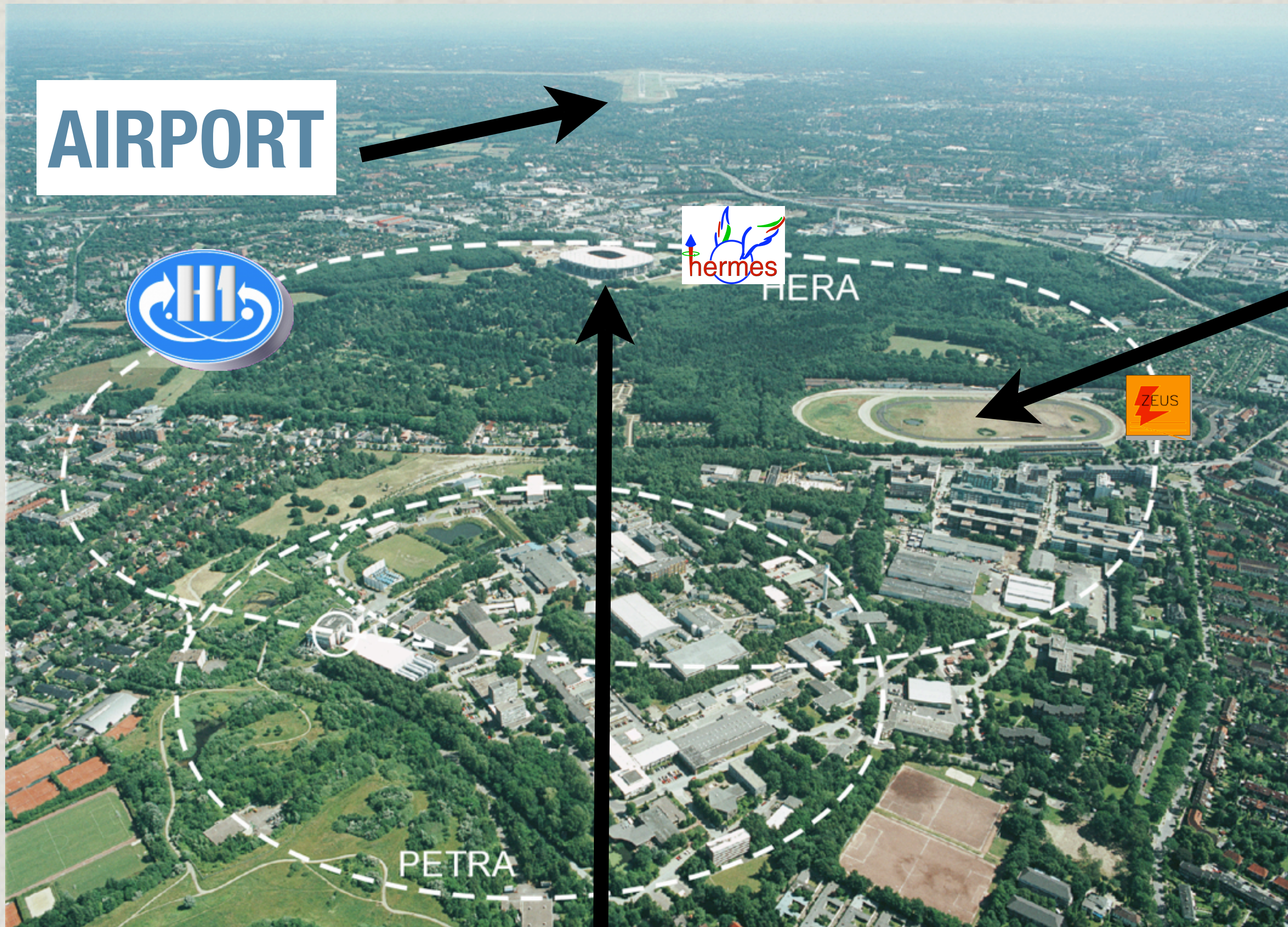
HERA & Hamburg



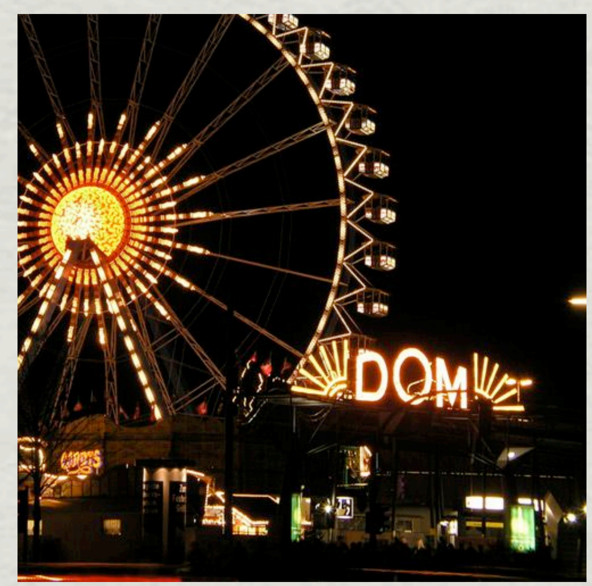
TRABRENNEN

HSV STADIUM

HERA & Hamburg

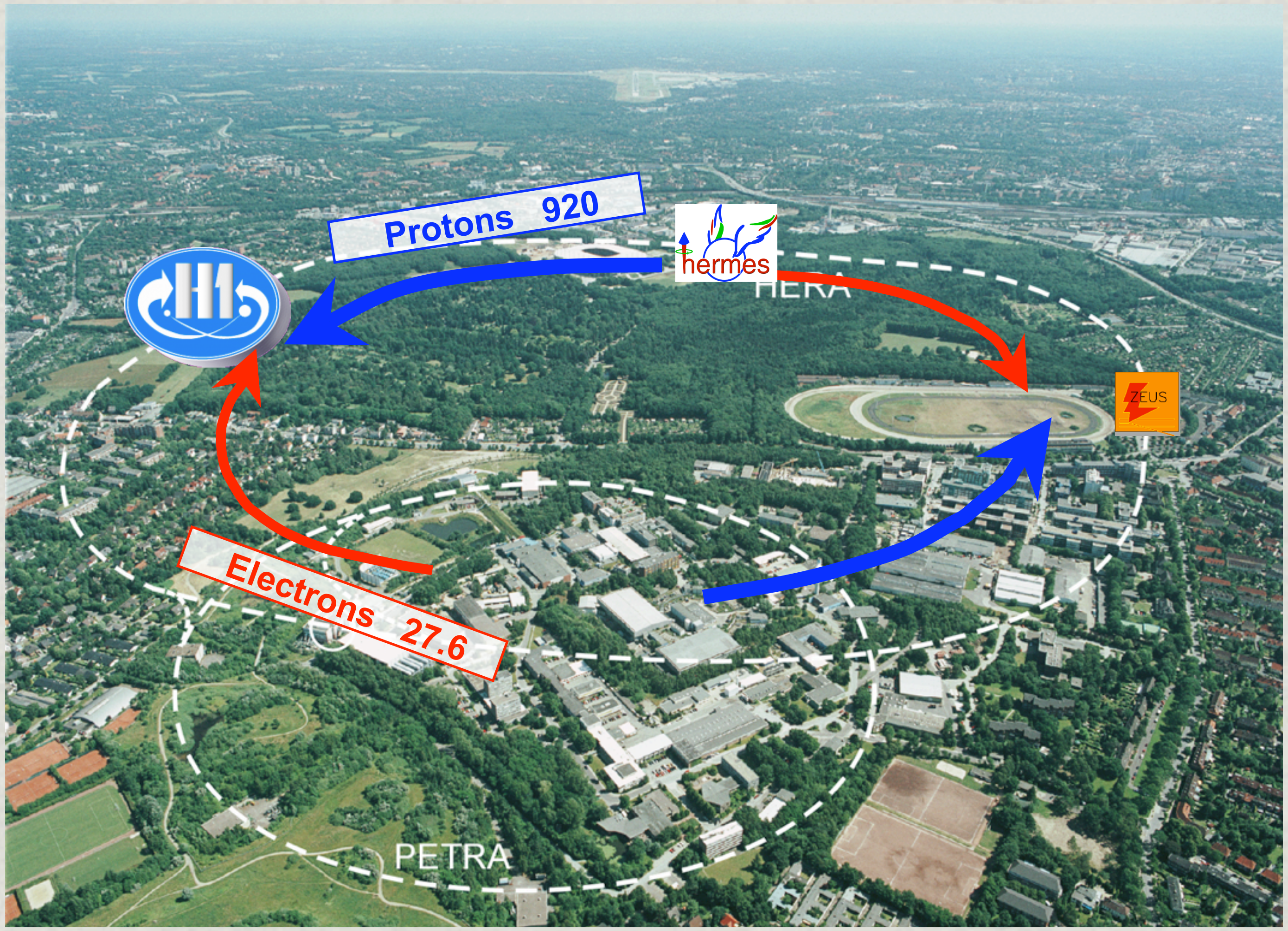


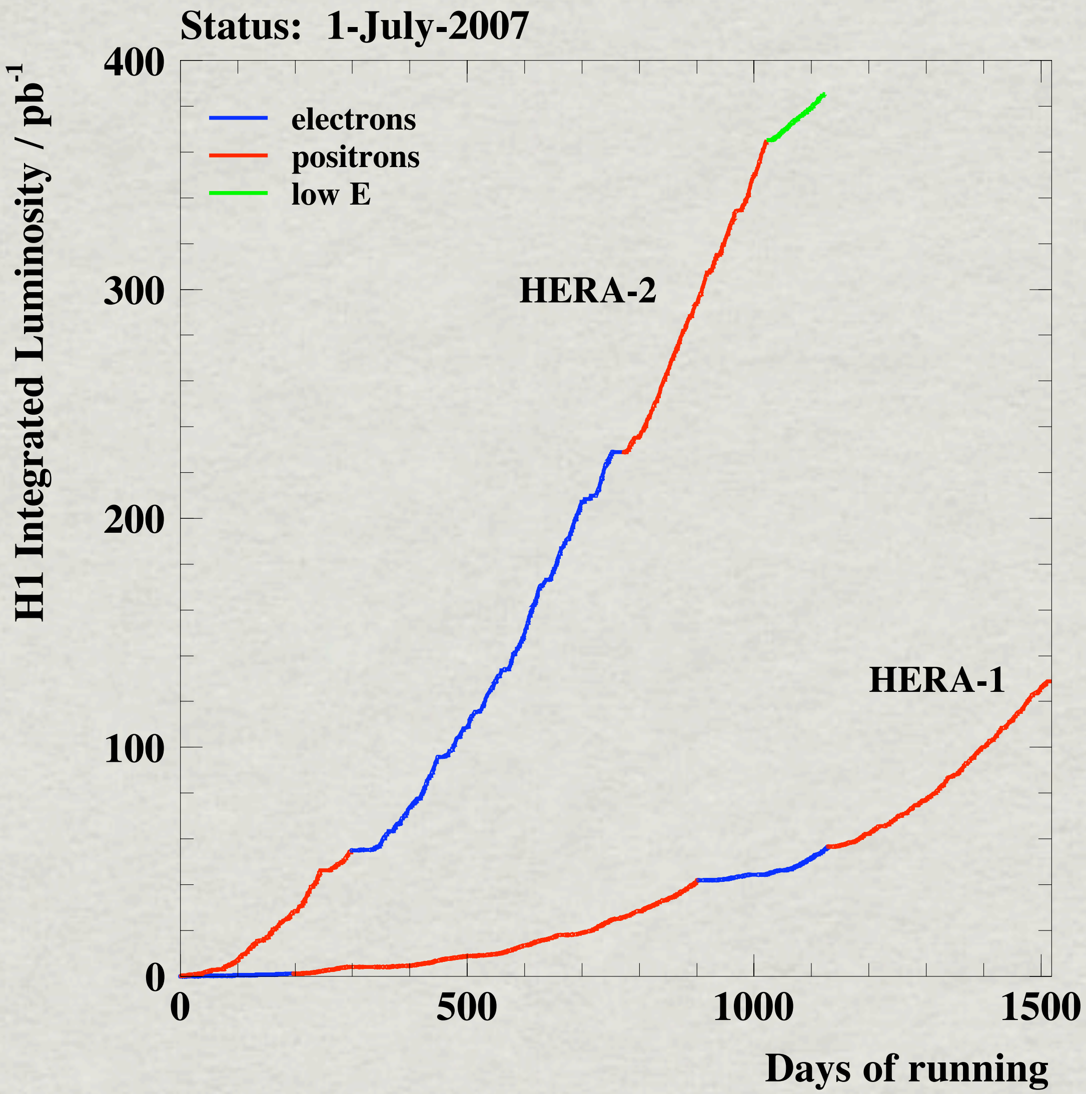
TRABRENNEN



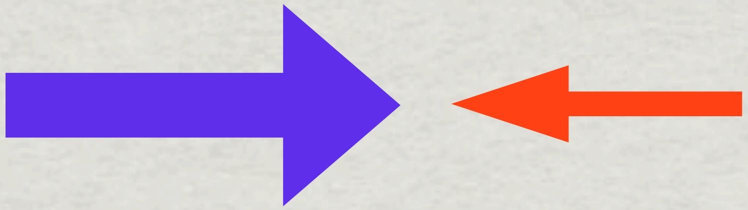
HSV STADIUM

HERA machine & physics





1992 - 2007



PROTON 920 GEV

$e^{\pm}$ 27.5 GEV

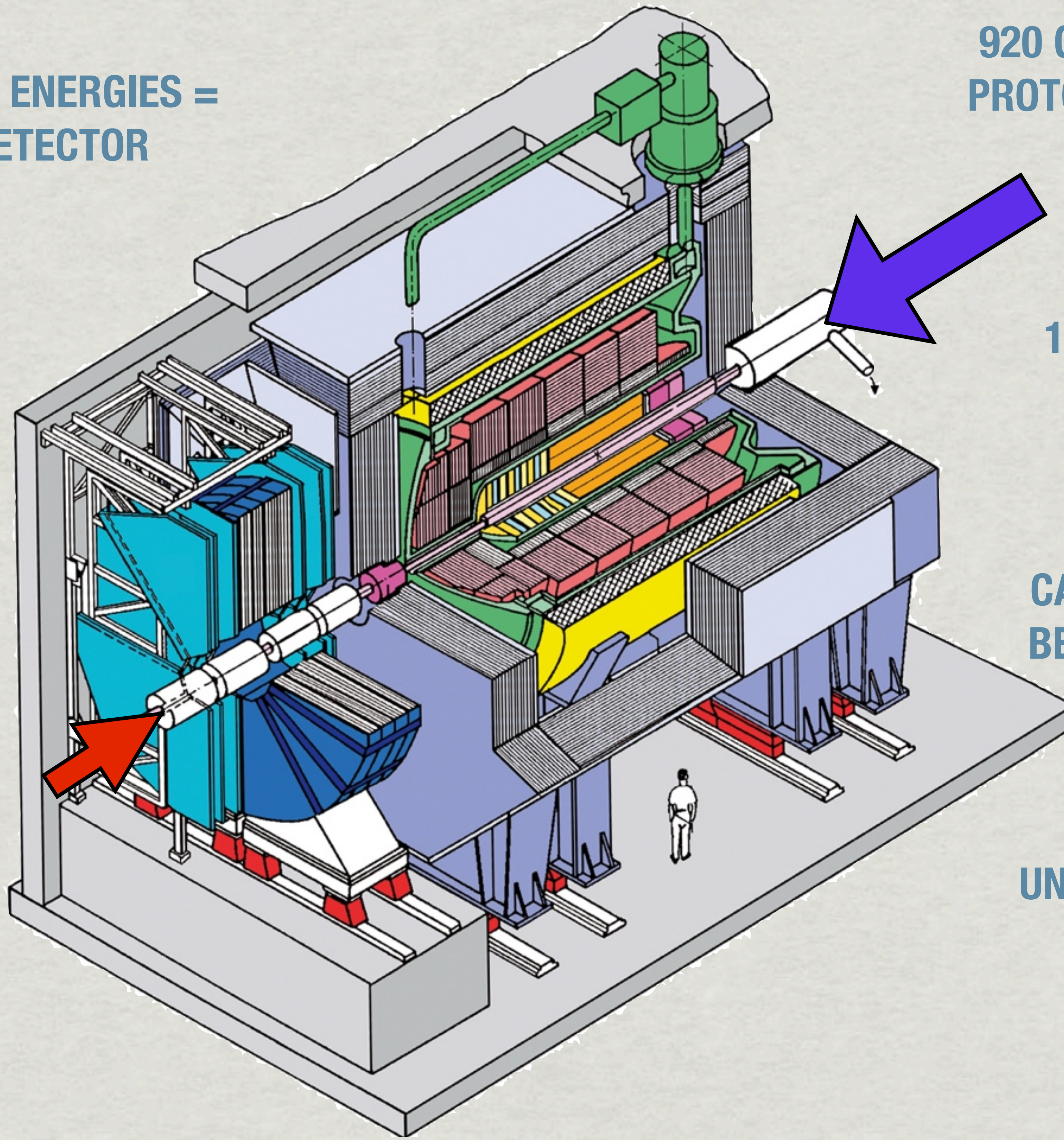
~0.5 fb^{-1} PER EXPERIMENT

+ LOW ENERGY PROTON RUN TO MEASURE F_L

The H1 Detector

ASYMMETRIC BEAM ENERGIES = ASYMMETRIC DETECTOR

920 GEV PROTONS



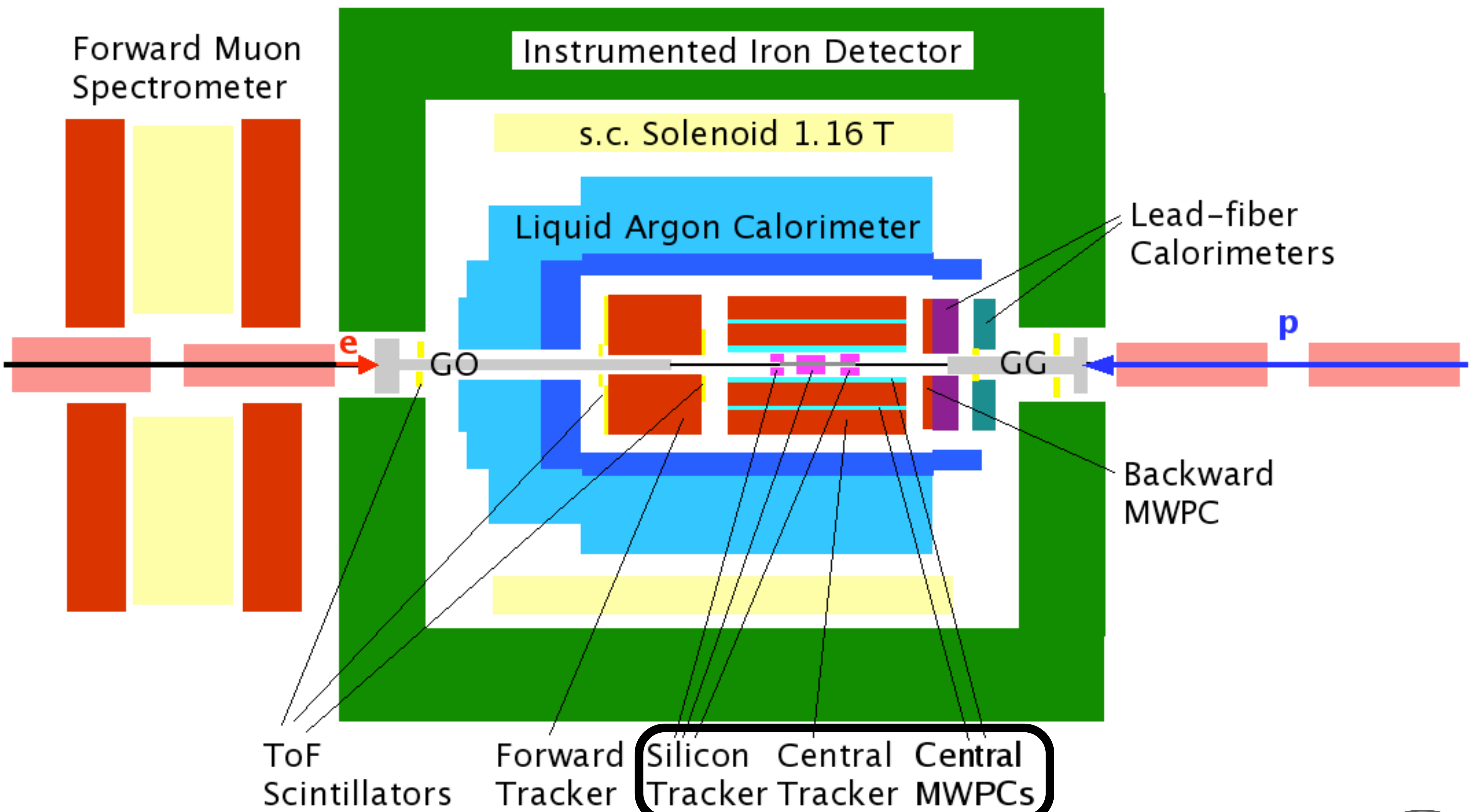
1.16 T SOLENOID, RADIUS 2.7 M (ALEPH LIKE)

COIL OUTSIDE CALORIMETER FOR BEST RESOLUTION!

27.5 GEV ELECTRONS

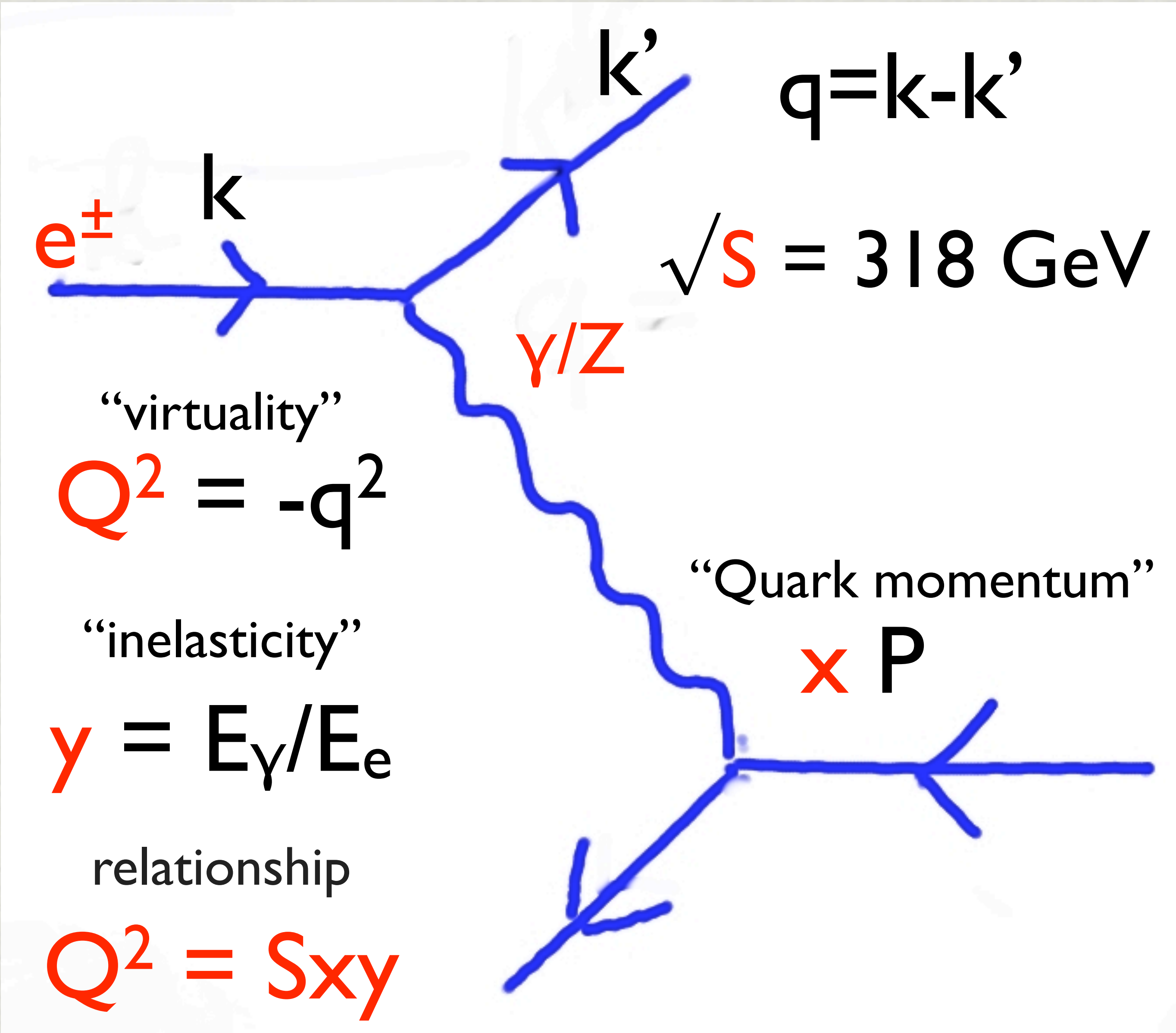
UNIFORM FIELD FOR TRACKING (CENTRAL AND FORWARD)!

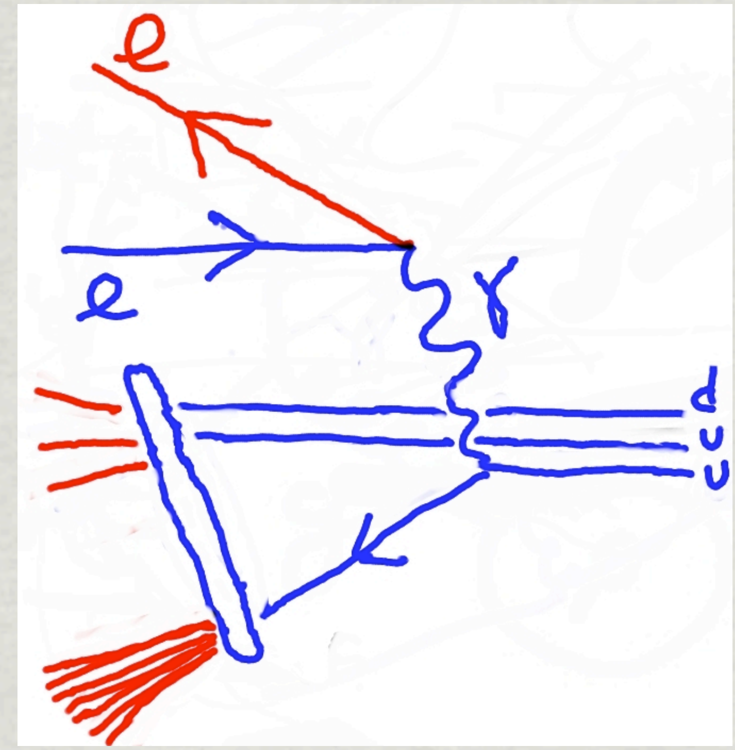
The H1 Detector

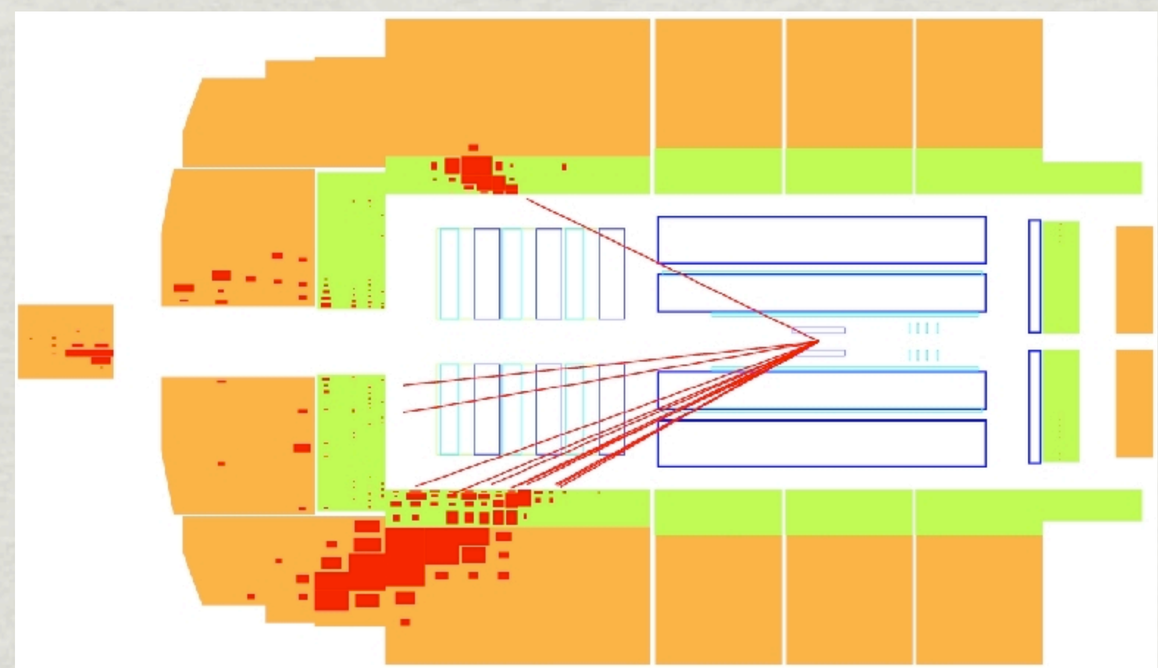


$\pm$ 1.74 η, p_t > 0.12 GeV

DIS







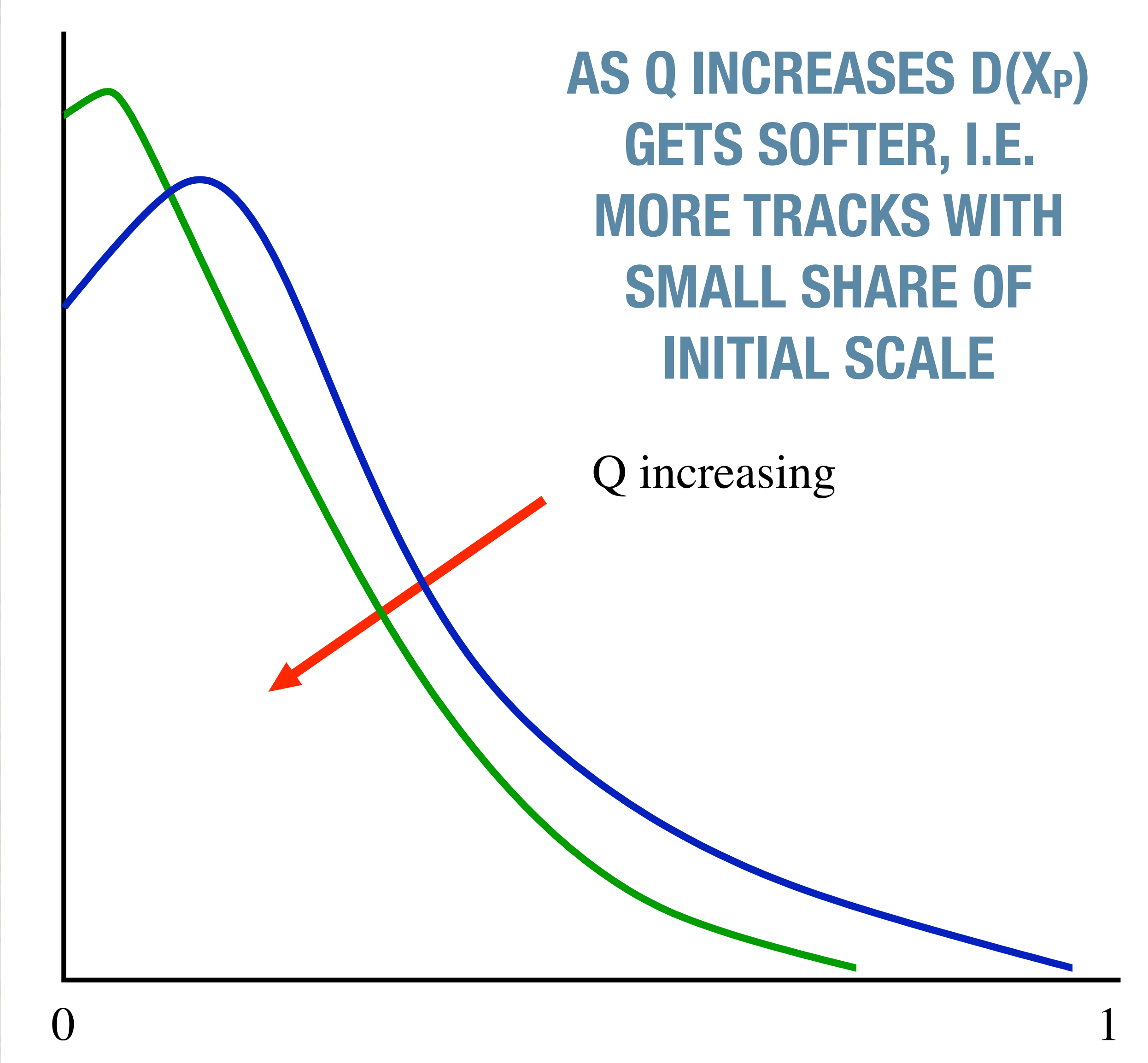
DIS, BORN LEVEL

Fragmentation Functions

Fragmentation Function

$$x_p = \frac{(2P_h)}{Q}$$

$$D(x_p) = \frac{1}{N_{event}} dn/dx_p$$



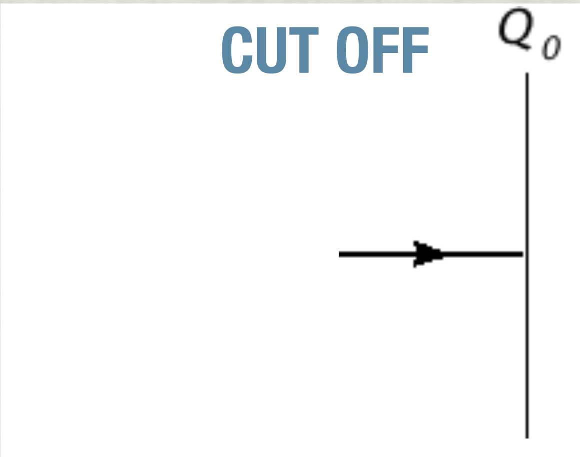
X_P = SCALED MOMENTUM VARIABLE

Q/2 = SCALE IN CURRENT REGION OF BREIT FRAME

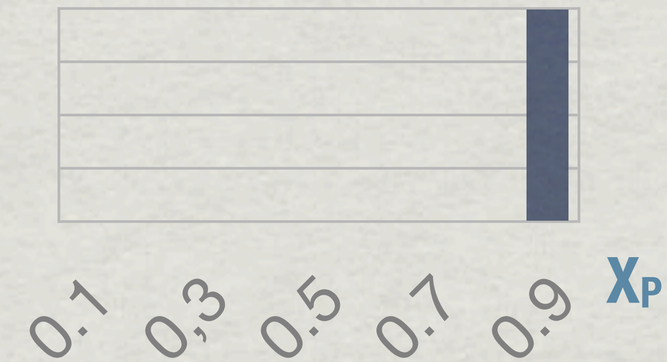
P_H = MOMENTUM OF CHARGED PARTICLE IN CURRENT REGION OF BREIT FRAME

$D(X_P)$ = EVENT NORMALISED, CHARGED PARTICLE, SCALED MOMENTUM DISTRIBUTION

Scaling Violations



Q ~ Q_0, NO ROOM FOR GLUON EMISSION



Q INCREASING

DGLAP SPLITTING FUNCTION

$$P_{ji}(x_p, \alpha_s) = P_{ji}^{(0)}(x_p) + \frac{\alpha_s}{2\pi} P_{ji}^{(1)}(x_p) + \ldots$$

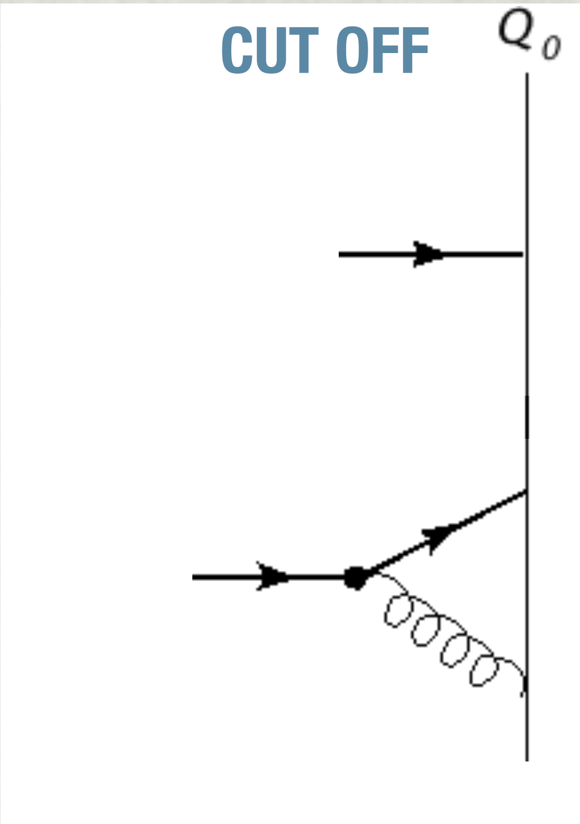
$$\alpha_s(Q) \sim \frac{2\pi}{7ln(Q/\Lambda)}$$

SCALING VIOLATIONS, A PREDICTION OF QCD, SENSITIVE TO α_s

PETRA / SLC / LEP

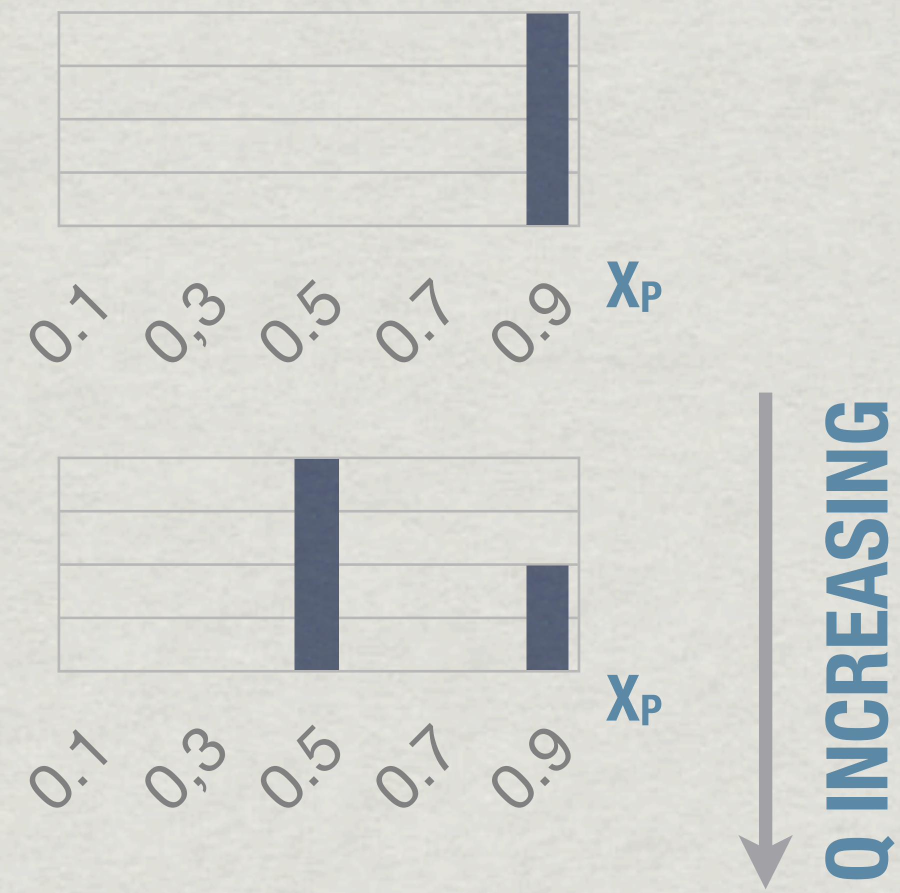
LOG DEPENDENCE ON Q

Scaling Violations



Q ~ Q_0, NO ROOM FOR GLUON EMISSION

Q > Q_0, PROBABILITY OF GLUON EMISSION (E.G. 50%, 1/2 P)



DGLAP SPLITTING FUNCTION

$$P_{ji}(x_p, \alpha_s) = P_{ji}^{(0)}(x_p) + \frac{\alpha_s}{2\pi} P_{ji}^{(1)}(x_p) + \ldots$$

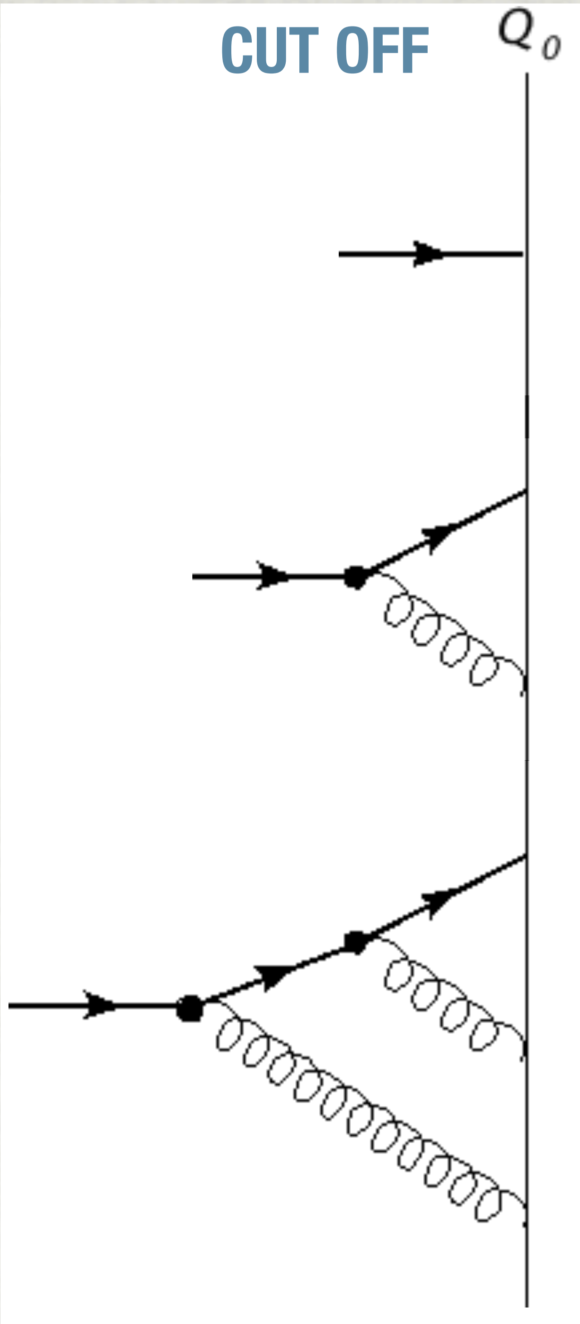
$$\alpha_s(Q) \sim \frac{2\pi}{7ln(Q/\Lambda)}$$

SCALING VIOLATIONS, A PREDICTION OF QCD, SENSITIVE TO α_s

PETRA / SLC / LEP

LOG DEPENDENCE ON Q

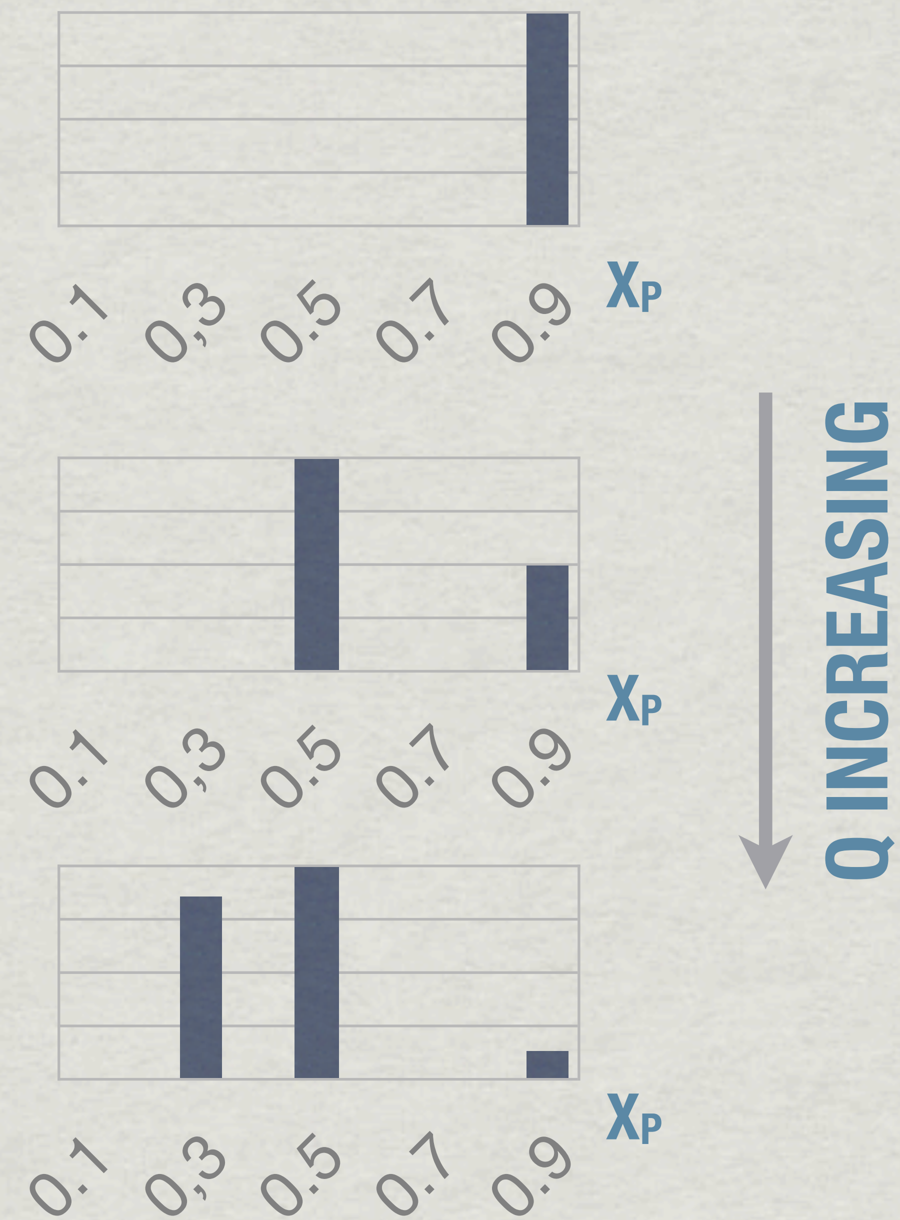
Scaling Violations



Q ~ Q_0, NO ROOM FOR GLUON EMISSION

Q > Q_0, PROBABILITY OF GLUON EMISSION (E.G. 50%, 1/2 P)

Q >> Q_0, ROOM FOR MORE EMISSIONS



DGLAP SPLITTING FUNCTION

$$P_{ji}(x_p, \alpha_s) = P_{ji}^{(0)}(x_p) + \frac{\alpha_s}{2\pi} P_{ji}^{(1)}(x_p) + \ldots$$

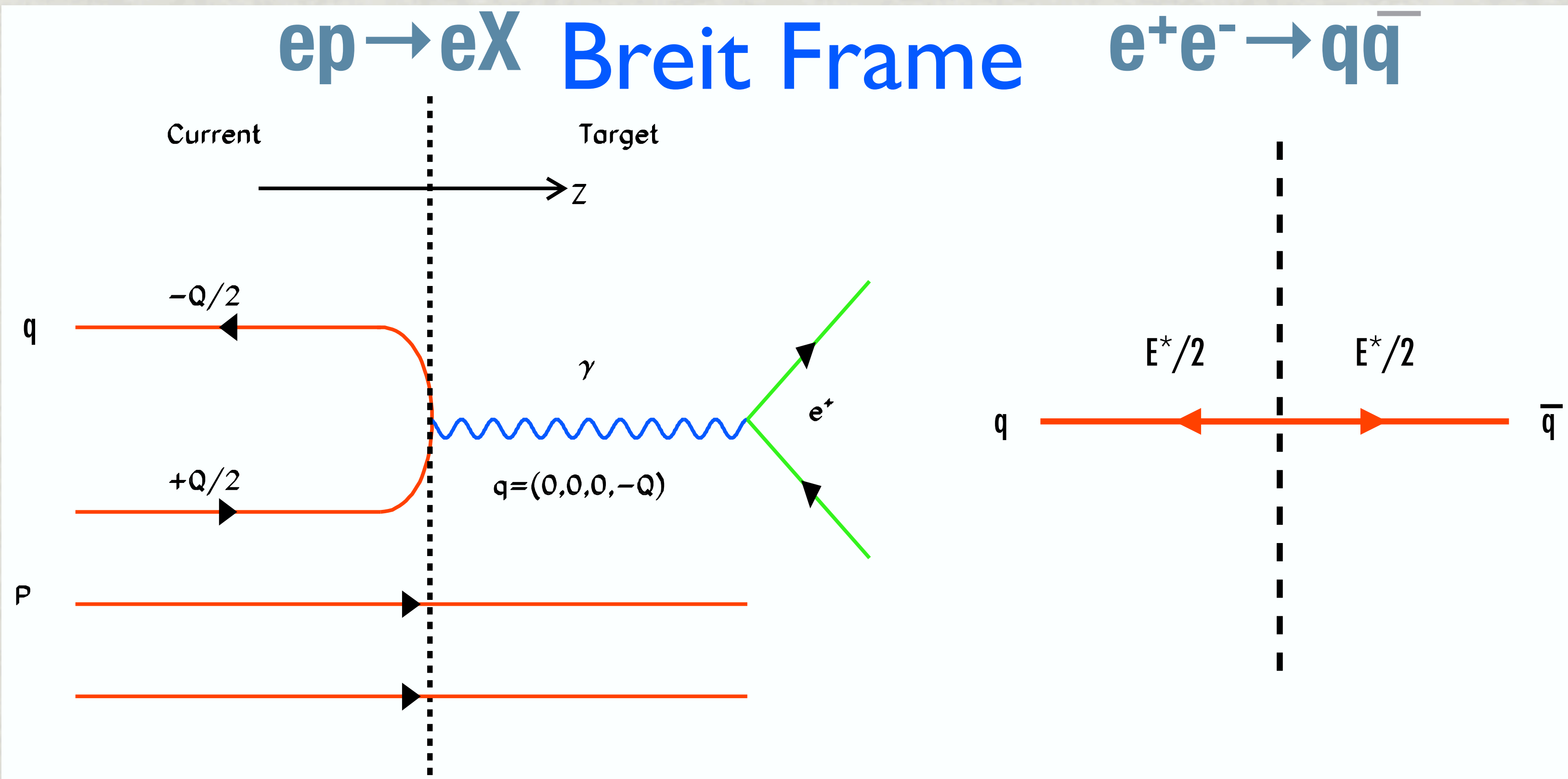
$$\alpha_s(Q) \sim \frac{2\pi}{7ln(Q/\Lambda)}$$

SCALING VIOLATIONS, A PREDICTION OF QCD, SENSITIVE TO α_s

PETRA / SLC / LEP

LOG DEPENDENCE ON Q

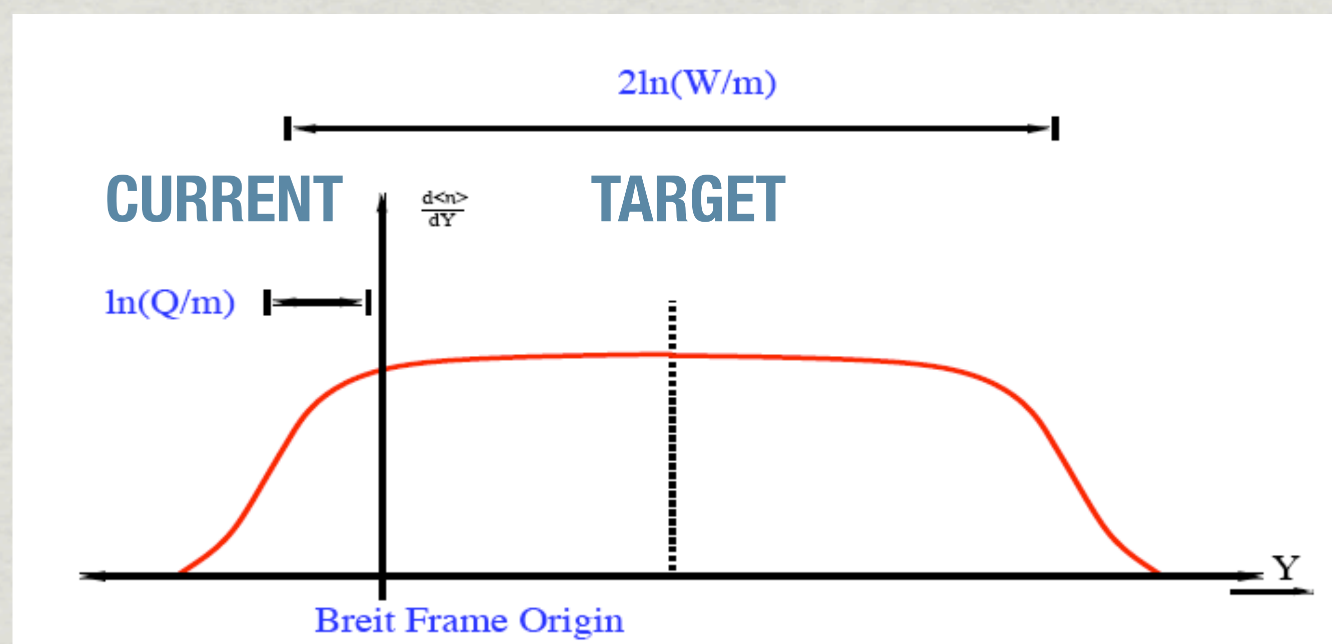
The Brit Frame



PROVIDES CLEAREST SEPARATION BETWEEN PARTICLES FROM HARD SCATTERING AND PROTON REMNANT. ALLOWS FOR EASY COMPARISON WITH e^+e^- DATA

CURRENT REGION ENERGY SCALE IS Q/2

BOOST TO BREIT FRAME MEANS WE MEASURE DOWN TO MOMENTUM =0!



Analysis basics

KINEMATIC PHASE SPACE

$100 < Q^2 < 20{,}000\ GeV^2$

$0.05 < y < 0.6$

$\theta_{ELECTRON} > 150°$

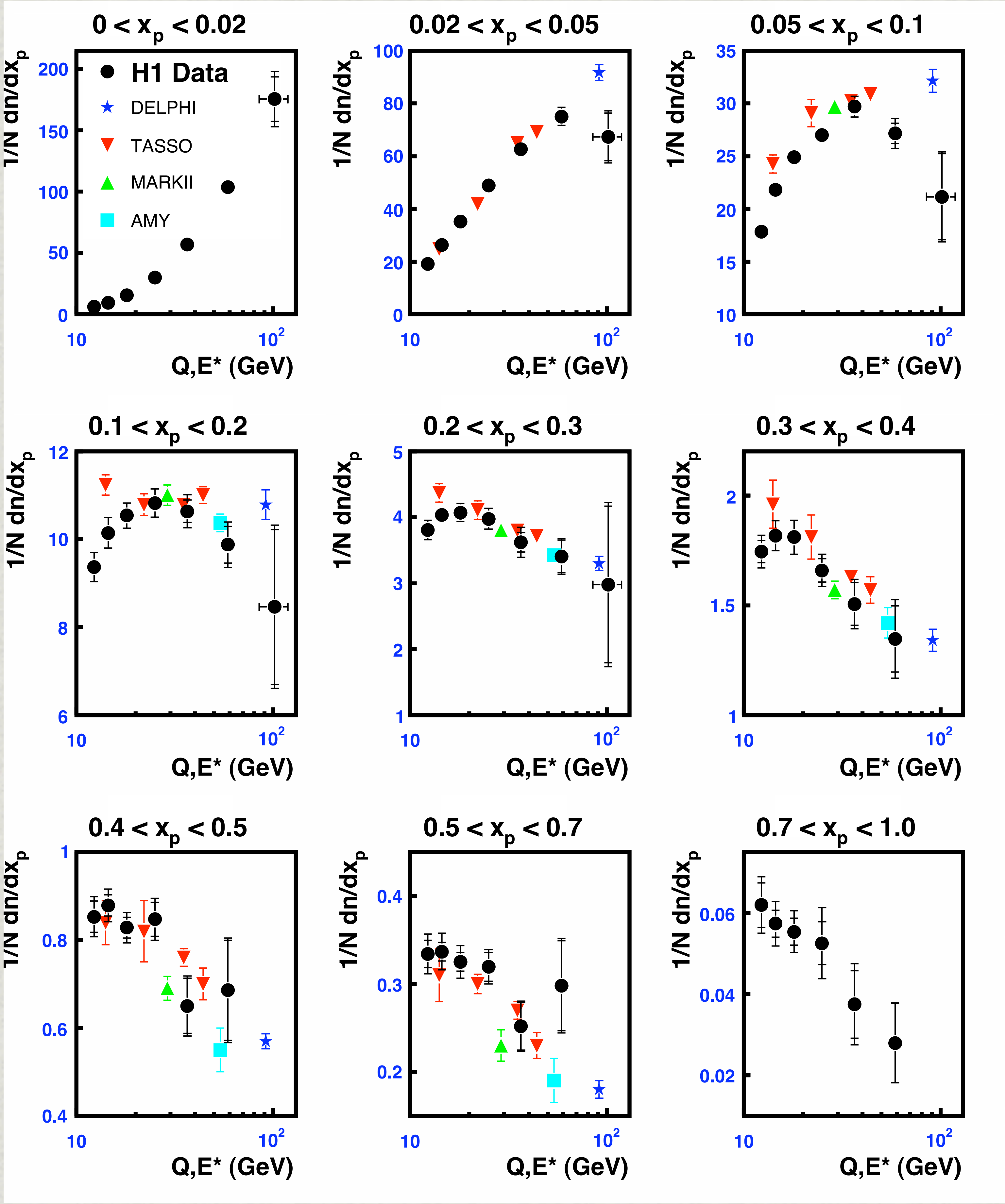
$30° < \theta_{Q,LAB} < 150°$

QUARK SCATTERING ANGLE, $\theta_{Q,LAB}$, CALCULATED FROM KINEMATICS.
ENSURES CURRENT REGION OF BREIT FRAME REMAINS WITHIN TRACKING ACCEPTANCE.
EASY TO CALCULATE IN THEORY!

CORRECTION FACTOR < 1.2. DOMINATED BY BOOST TO BREIT FRAME. CORRECTION FOR TRACKING EFFICIENCIES VERY SMALL

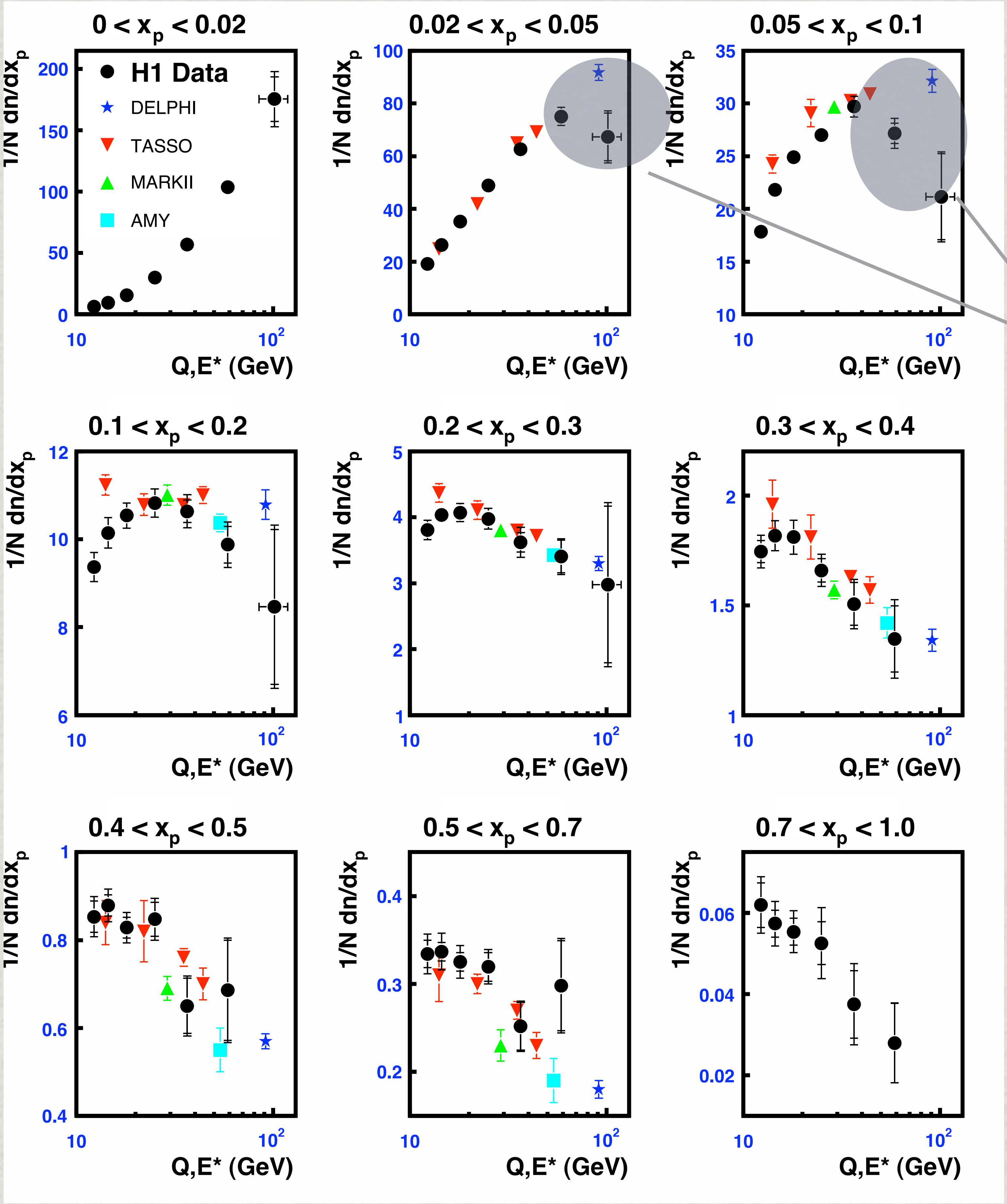
SYSTEMATIC ERROR ~5%

K^0, Λ, ETC.. CONSIDERED AS STABLE



PRETTY GOOD AGREEMENT BETWEEN ep AND e^+e^- !

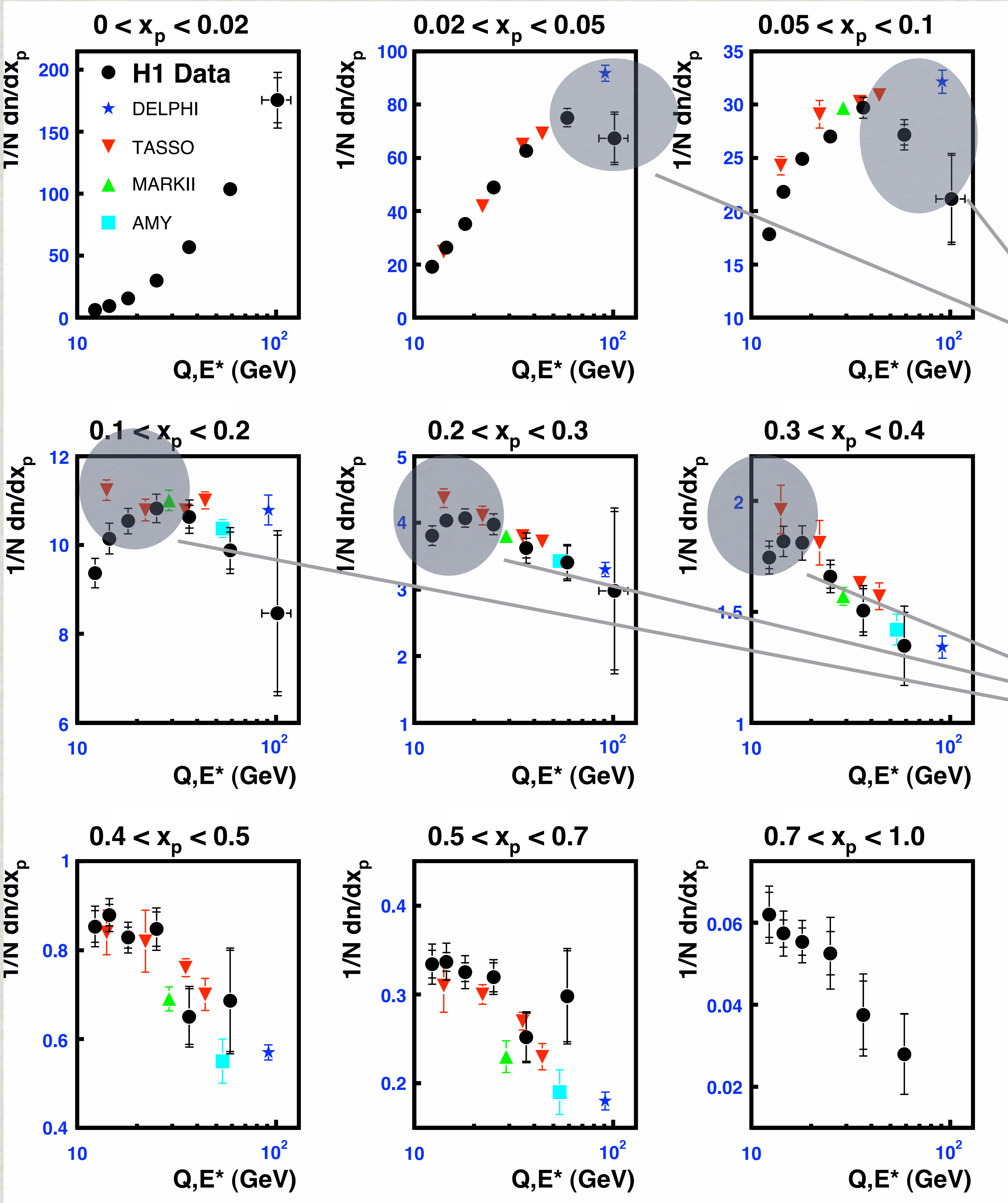
NB: SUPPRESSED ZEROS



PRETTY GOOD AGREEMENT BETWEEN ep AND e^+e^- !

LARGE DIFFERENCE AT HIGH Q AND SMALL X_P REASON UNCLEAR

NB: SUPPRESSED ZEROS



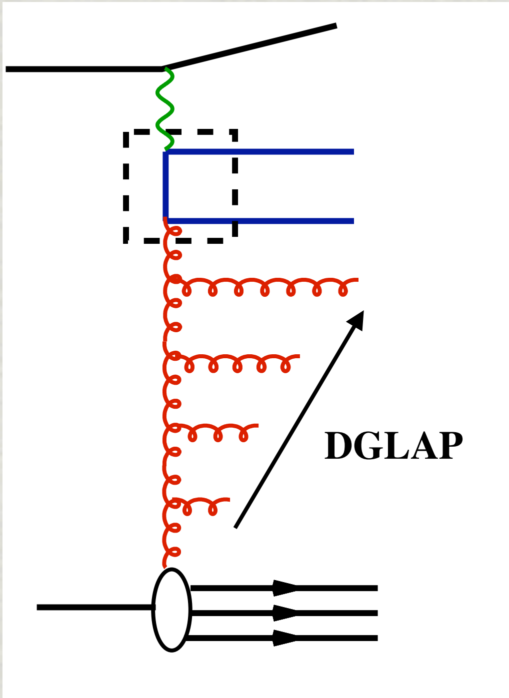
PRETTY GOOD AGREEMENT BETWEEN ep AND e^+e^- !

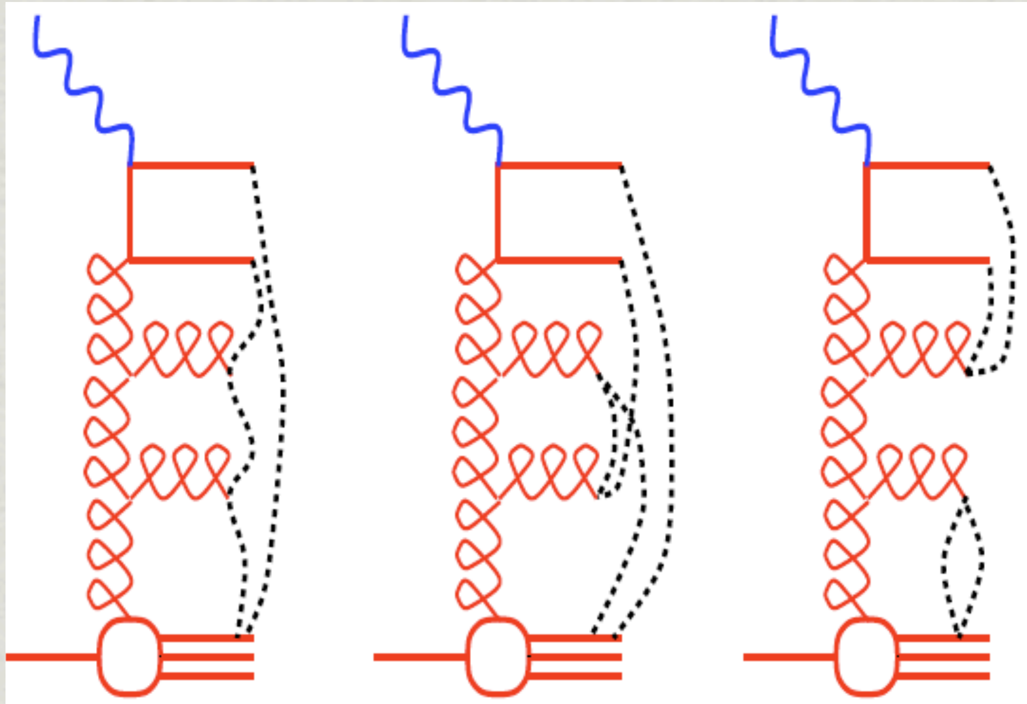
LARGE DIFFERENCE AT HIGH Q AND SMALL X_P REASON UNCLEAR

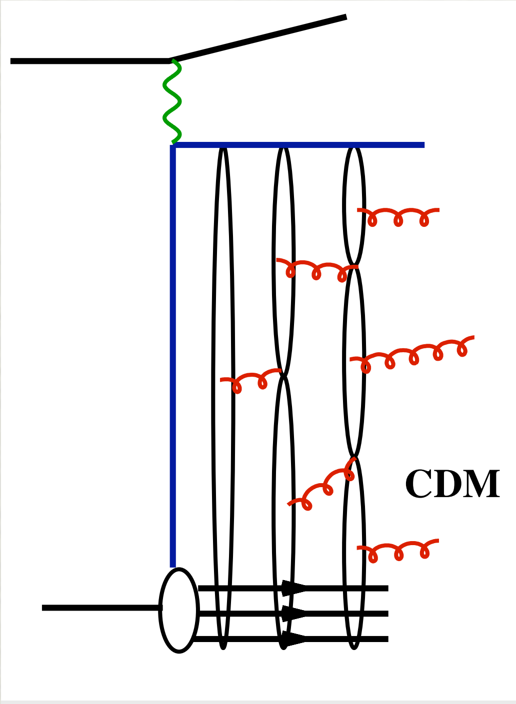
LOW Q, MID X_P. EXPECTED TO BE DUE TO BGF KINEMATICS PRODUCING EMPTY CURRENT REGION

NB: SUPPRESSED ZEROS

Monte Carlo Models







LEPTO (PARTON SHOWERS + STRING)

SCI (LEPTO + SOFT COLOUR INTERACTIONS)

ARIADNE (COLOUR DIPOLE MODEL + STRING)

DGLAP "LIKE"

BFKL "LIKE"

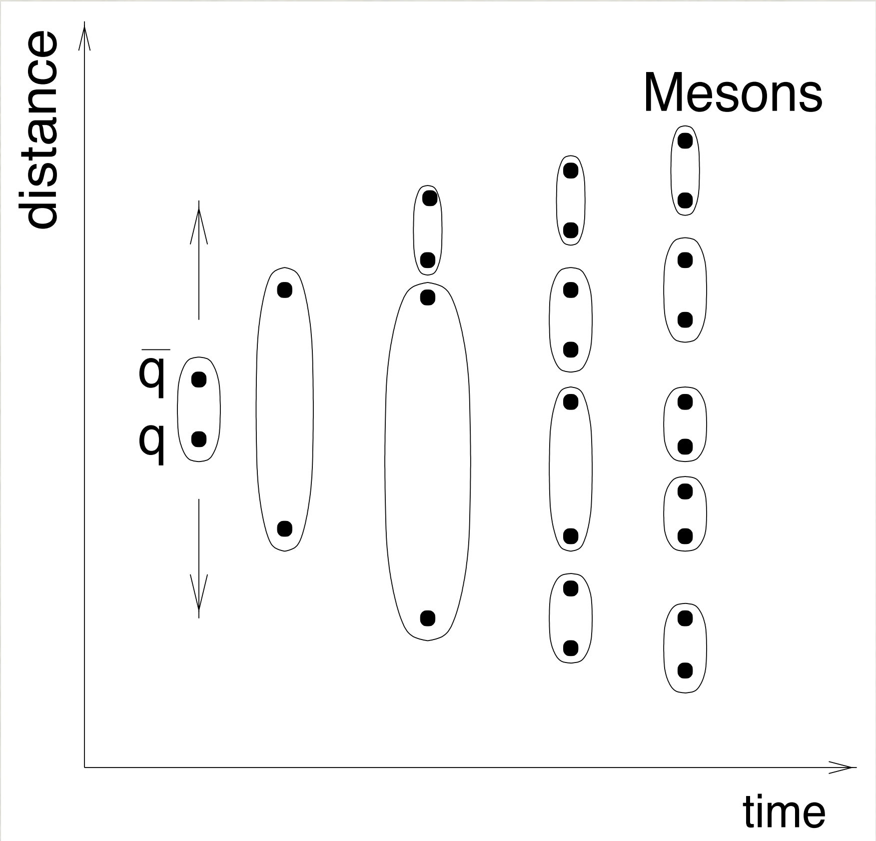
RESUM ln(Q^2) TERMS, ORDER PARTON EMISSION STRONGLY WITH K_T.

RESUM ln(1/X) TERMS, WEAK K_T ORDERING.

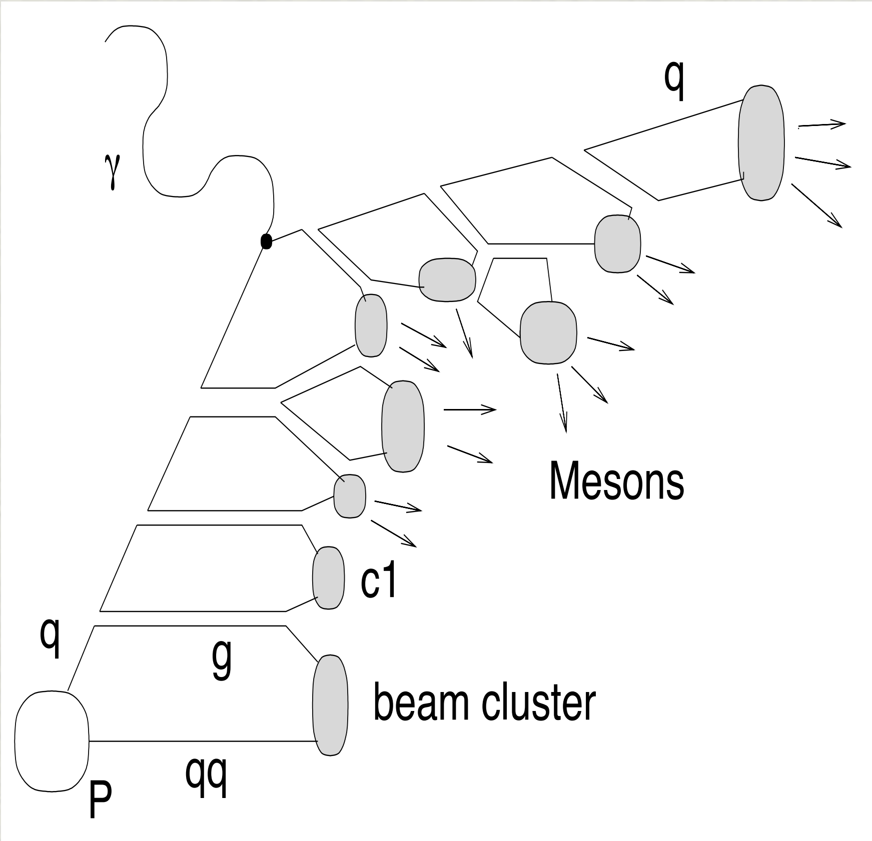
$$\sim \Sigma_{mn} A_{mn} ln(Q^2)^m ln(1/x)^n$$

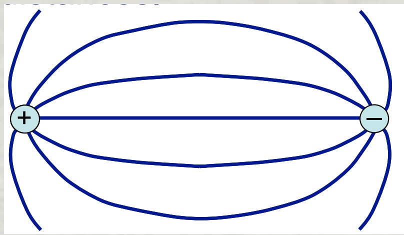
Hadronisation

LUND STRING HADRONISATION

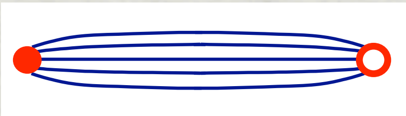


CLUSTER HADRONISATION (HERWIG)





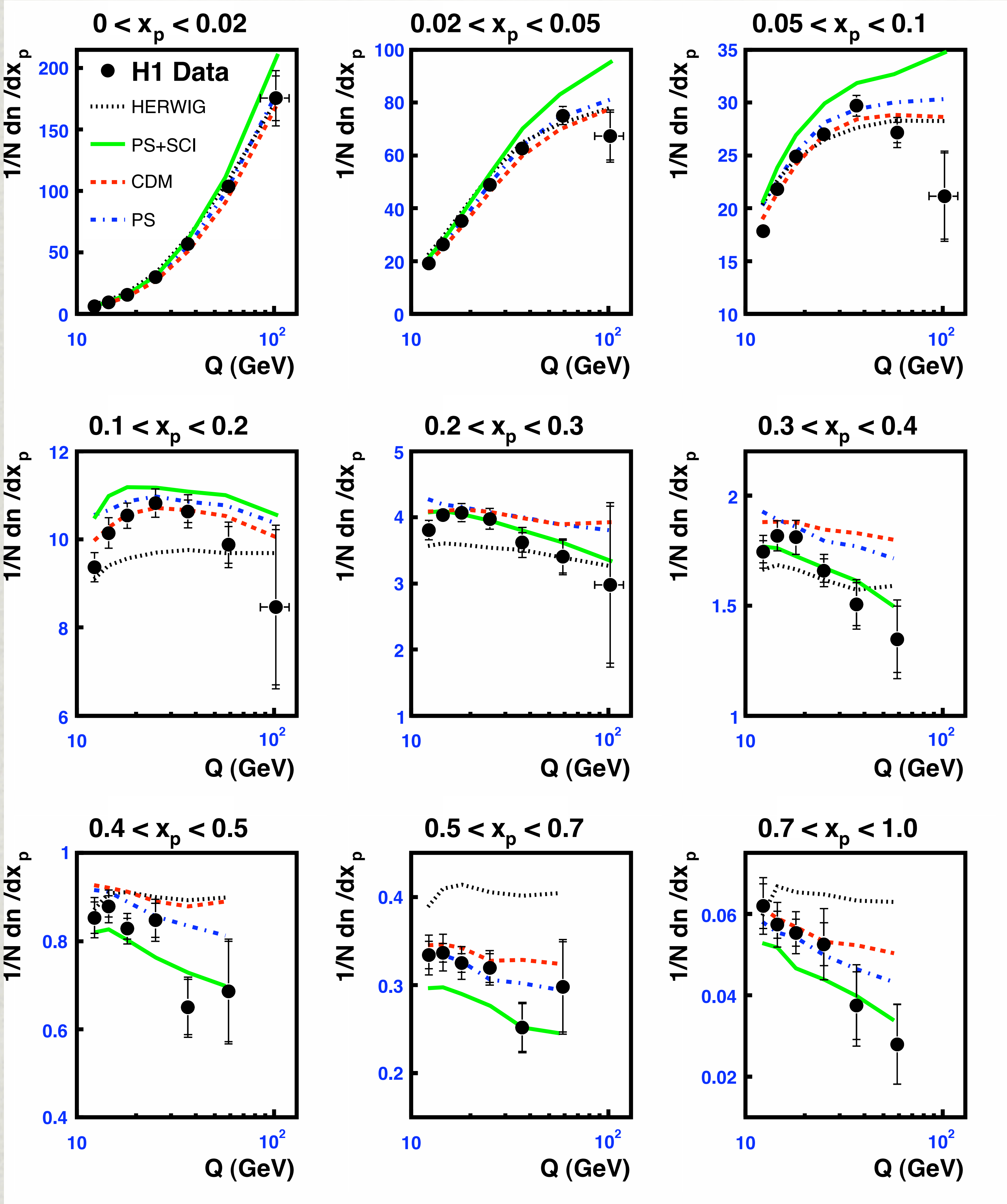
QED



QCD

LINEAR INTERQUARK POTENTIAL

THE PARTON SHOWER NATURALLY PRECONFINES COLOURED OBJECTS TOGETHER (CLUSTERS) WHICH CAN BE COMBINED INTO COLOURLESS MESONS

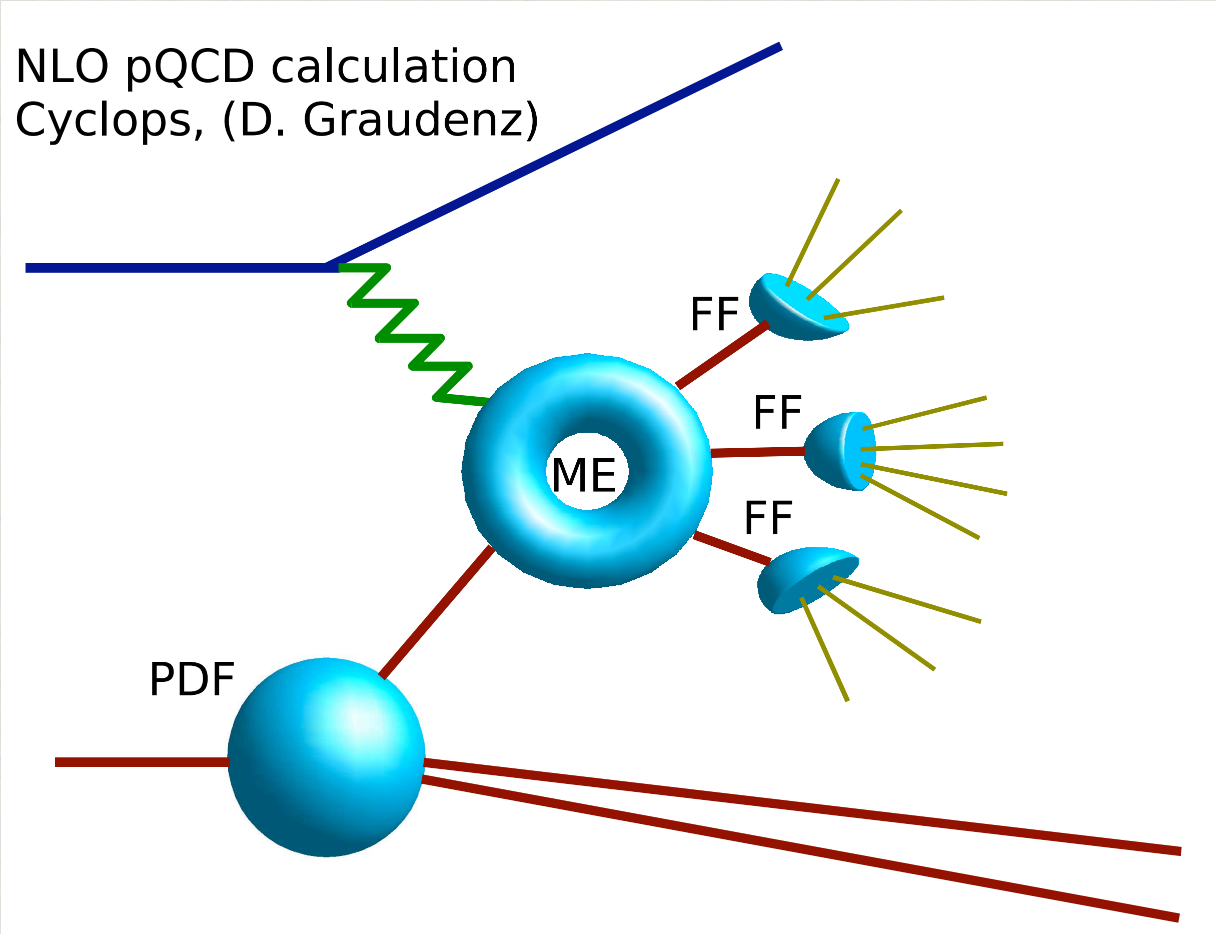


CDM AND PS ACCEPTABLE DESCRIPTION OF DATA. BOTH TEND TO OVERESTIMATE THE MULTIPLICITY AT HIGH Q

SCI MODEL PREDICTS TOO SOFT A SPECTRUM

HERWIG IS TOO HARD AND FAILS TO REPRODUCE SCALING VIOLATIONS SEEN IN THE DATA

Fragmentation Functions



NLO PQCD CYCLOPS

FRAGMENTATION FUNCTIONS - e+e- FITS

INFRA RED SAFE REGION (Q2>100), $X_P > 0.1$

FF PARAMETERISED FROM $X_P>0.1$

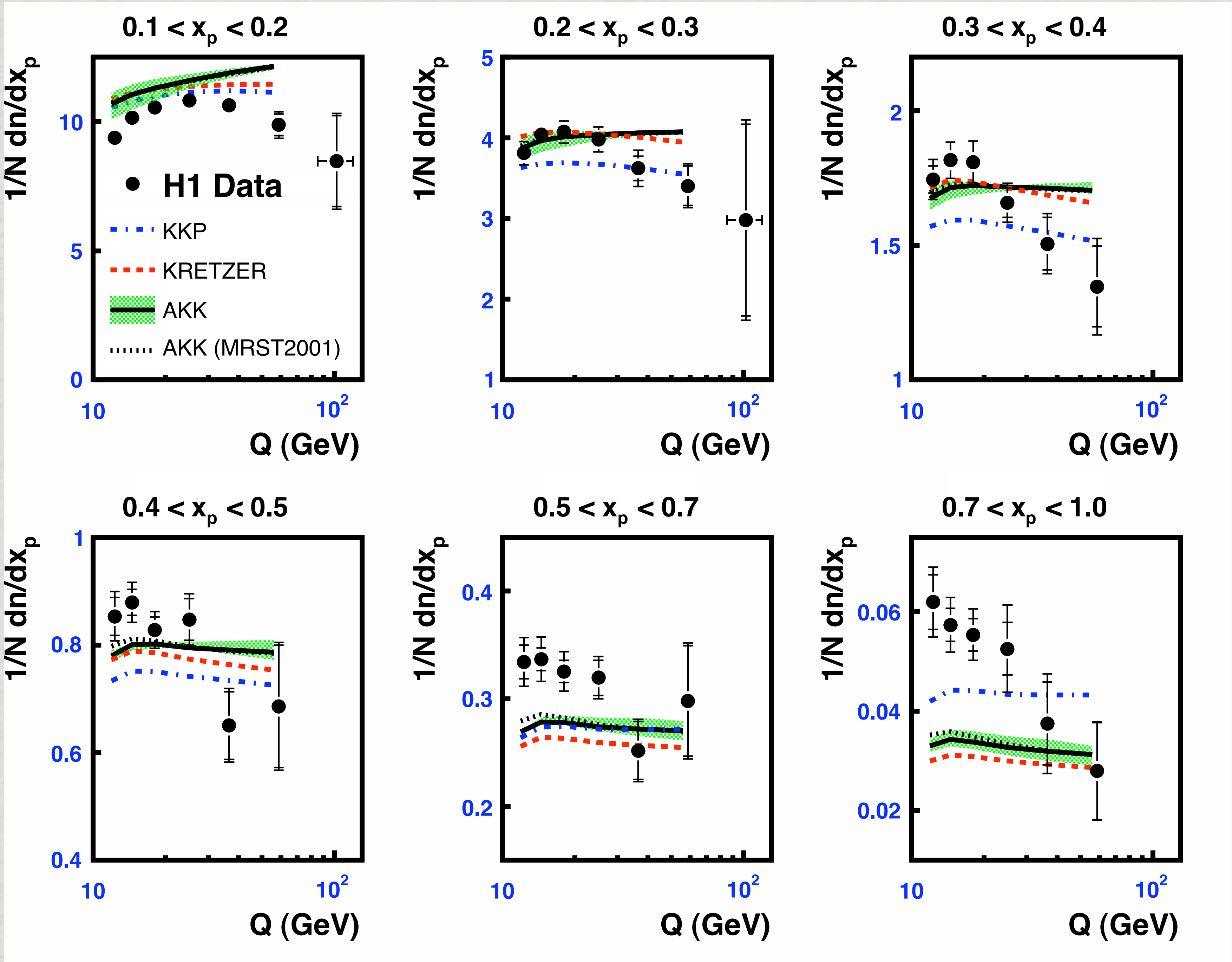
HIGHEST Q2 BIN (8,000 - 20,000) LOW IN STATISTICS.

σ_h = PDF ⊗ M.E. ⊗ FF

CTEQ6M, $\Lambda(5)$QCD = 226 MEV (ALSO ME + FF) $\sim\alpha_S$

$D^h_i(X_P,Q)$ GIVES THE DISTRIBUTION OF MOMENTUM FRACTION X_P FOR HADRONS OF TYPE h IN A JET INITIATED BY A PARTON OF TYPE i PRODUCED IN A HARD PROCESS AT SCALE Q

Comparison to NLO



FRAGMENTATION FUNCTIONS (KKP, KRETZER, AKK)TAKEN FROM FITS TO E+E- DATA

SCALE AND PDF ERRORS SMALL

SENSITIVITY TO DIFFERENT FF

NLO THEORY DOES NOT DESCRIBE THE DATA!

Strangeness in DIS

Analysis basics

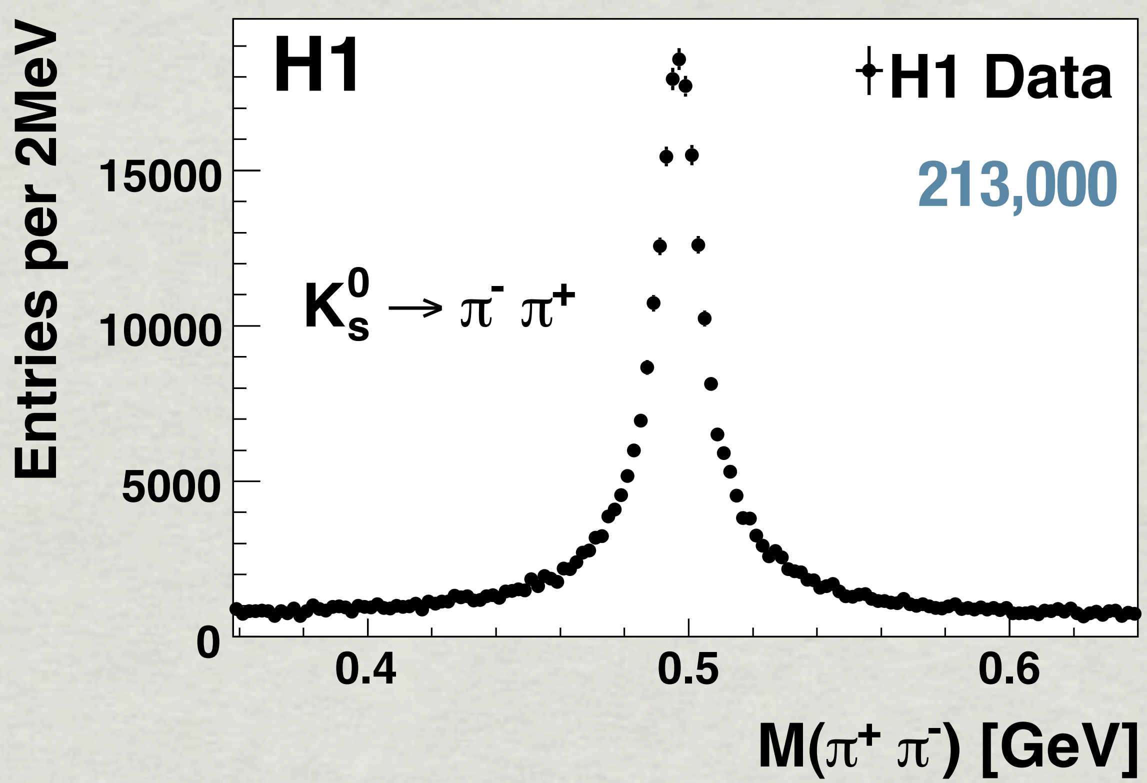
KINEMATIC PHASE SPACE

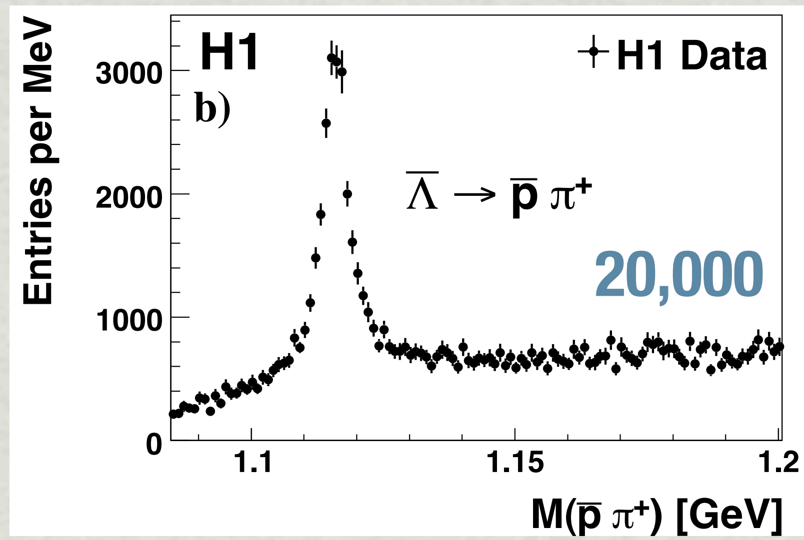
$2 < Q^2 < 100$ GeV^2

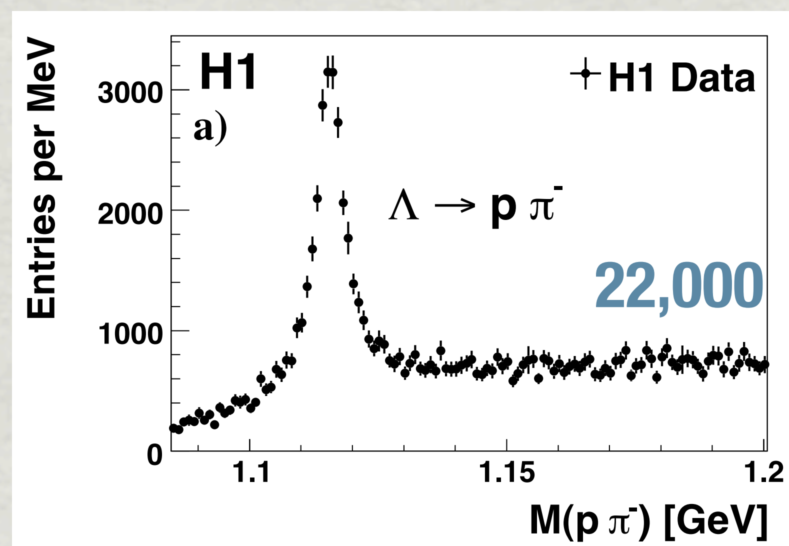
$0.05 < y < 0.6$

$0.5 < P_{T,K^0,\Lambda} < 3.5$ GeV

$|\eta_{K^0,\Lambda}| < 1.3$



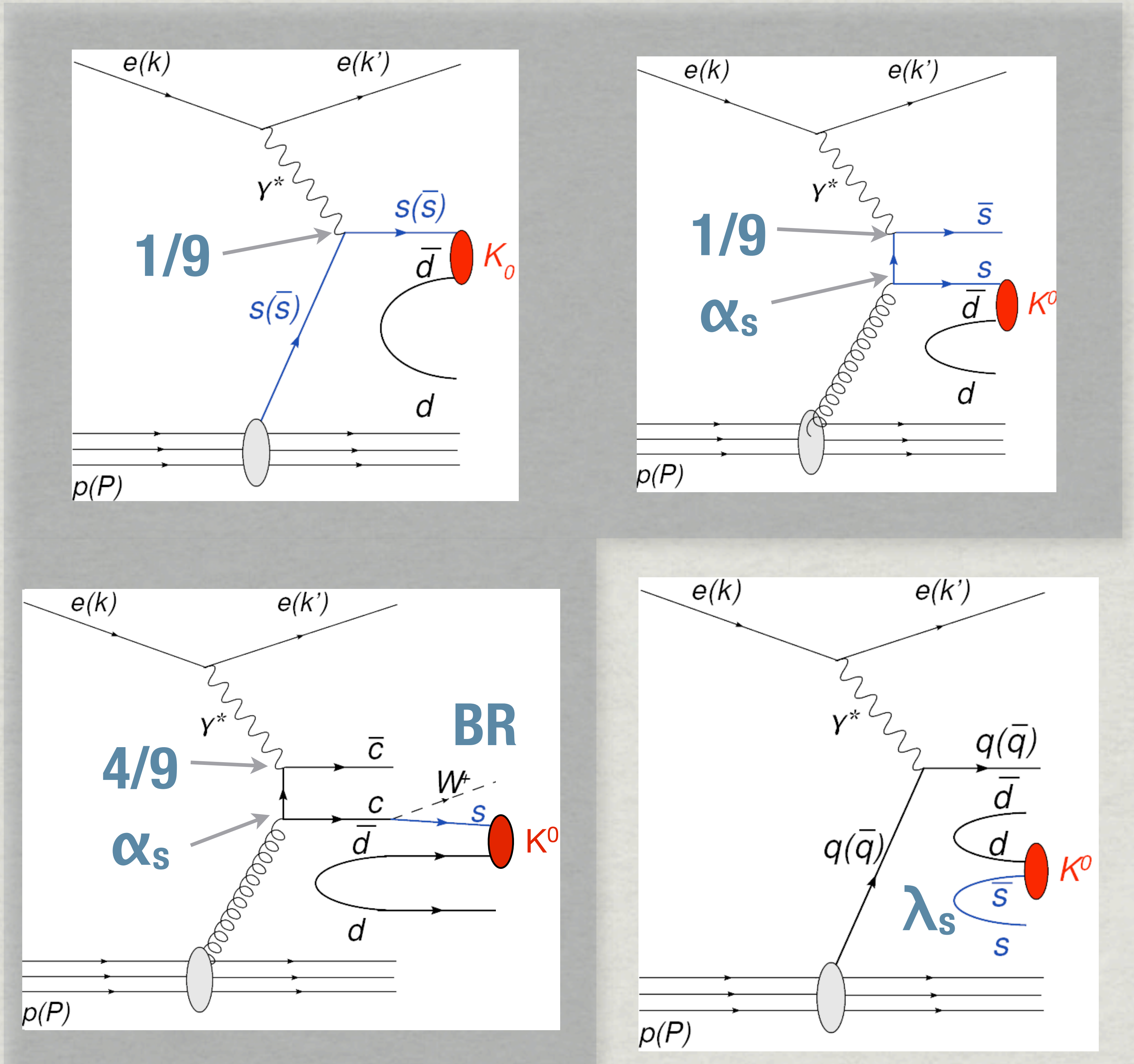




DOUBLE GAUSSIAN + LINEAR BACKGROUND

DOUBLE GAUSSIAN + BACKGROUND

Strangeness K^0



<u>SUPPRESSION</u>

q = 1/3, α_s

BRANCHING FRACTIONS

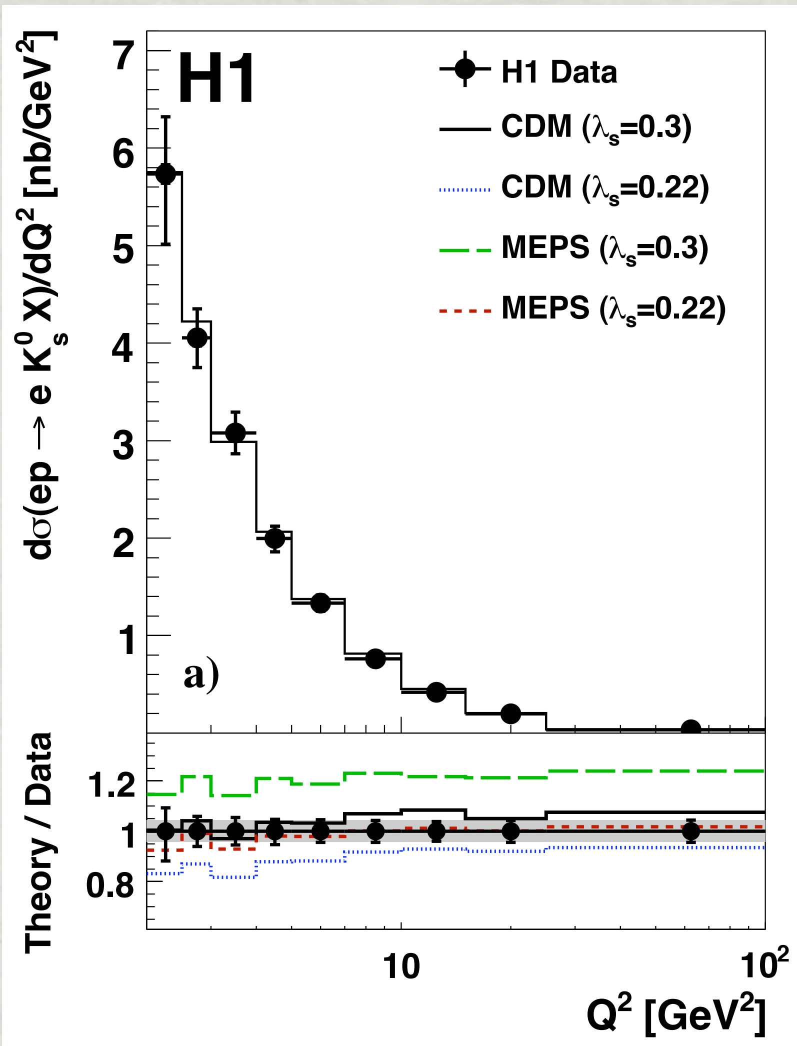
FRAGMENTATION λ_s

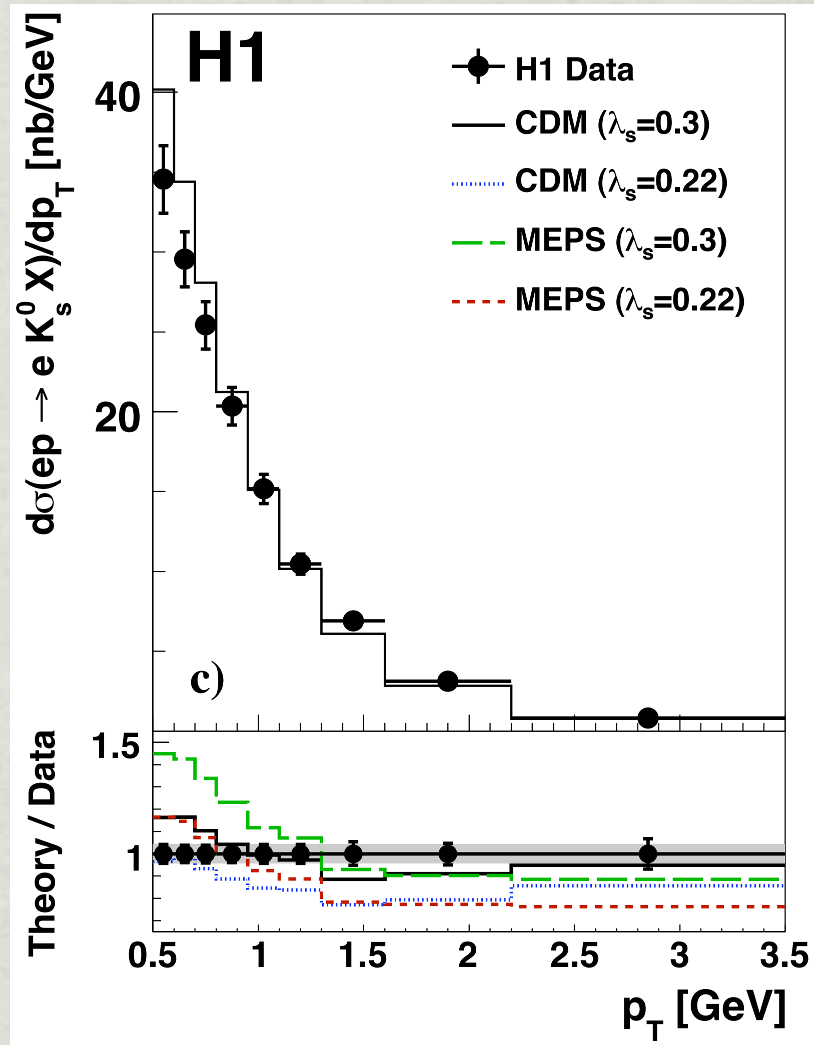
25% FROM THE HARD INTERACTION

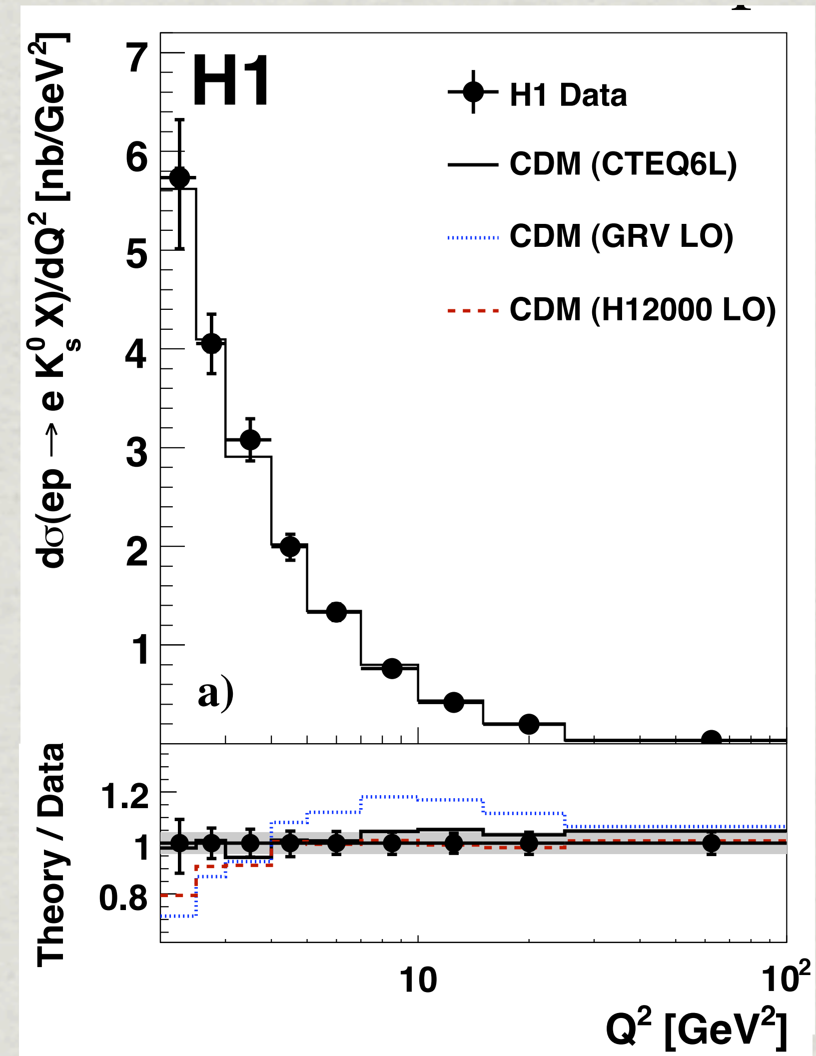
STRANGENESS SUPPRESSION FACTOR, λ_s, THE PROBABILITY OF CREATING A STRANGE QUARK COMPARED TO u OR d IN THE NON-PERTURBATIVE PROCESS

EXPECT λ_s TO BE UNIVERSAL; ALEPH TUNE, λ_s = 0.286,

Strangeness K^0







PS - λ_s ~ 0.22

CDM - λ_s ~ 0.3

P_T SHAPE WRONG FOR ALL

SOME PDF DEPENDENCE

SIMILAR STORY FOR OTHER VARIABLES;
η, X_{BJ}, BERIT FRAME, ETC...

NO ONE MODEL OR λ_s CAN DESCRIBE ALL DATA

CDM - λ_s ~ 0.3 PREFERRED

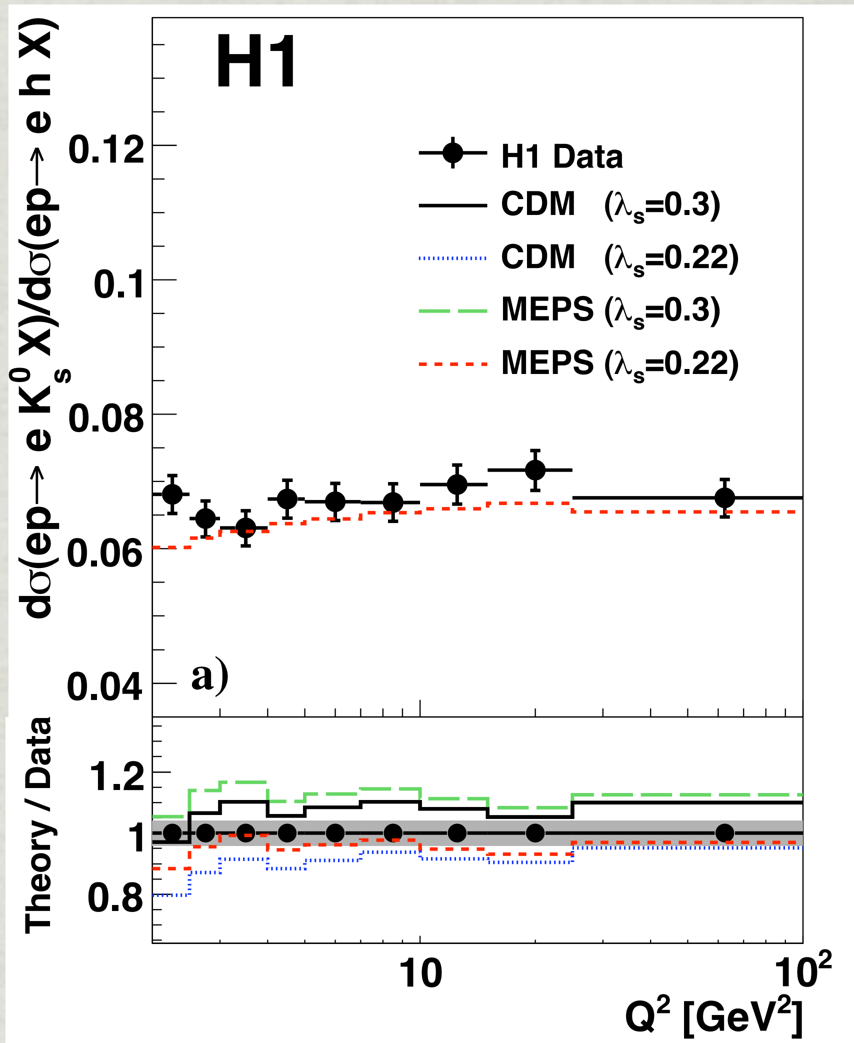
Strangeness K^0

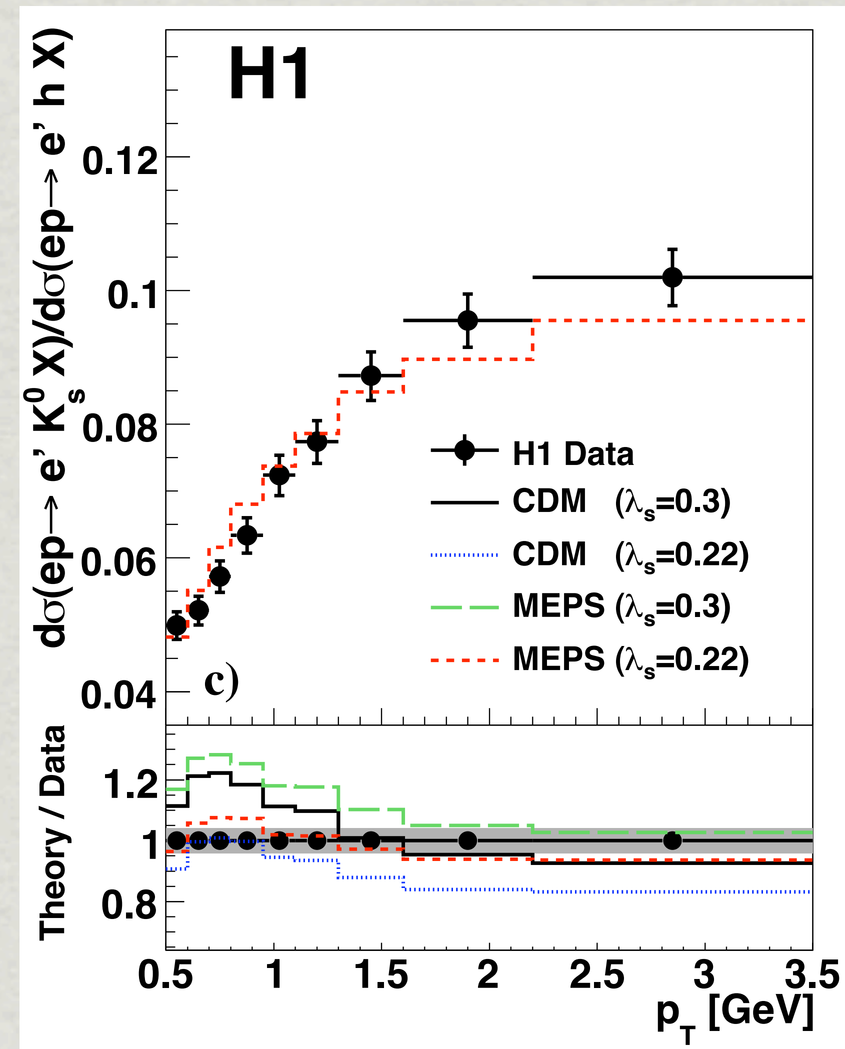
ep PHYSICS MORE COMPLICATED THAN e^+e^-, MAY CAUSE SOME OF THE DIFFERENCE

TAKE RATIO OF K^0 TO ALL CHARGED PARTICLES (~π)

ONLY THE DIFFERENCES IN PARTICLE PRODUCTION BETWEEN ud AND s LEFT

BOTH PS AND CDM SIMILAR PREDICTIONS FOR SIMILAR λs

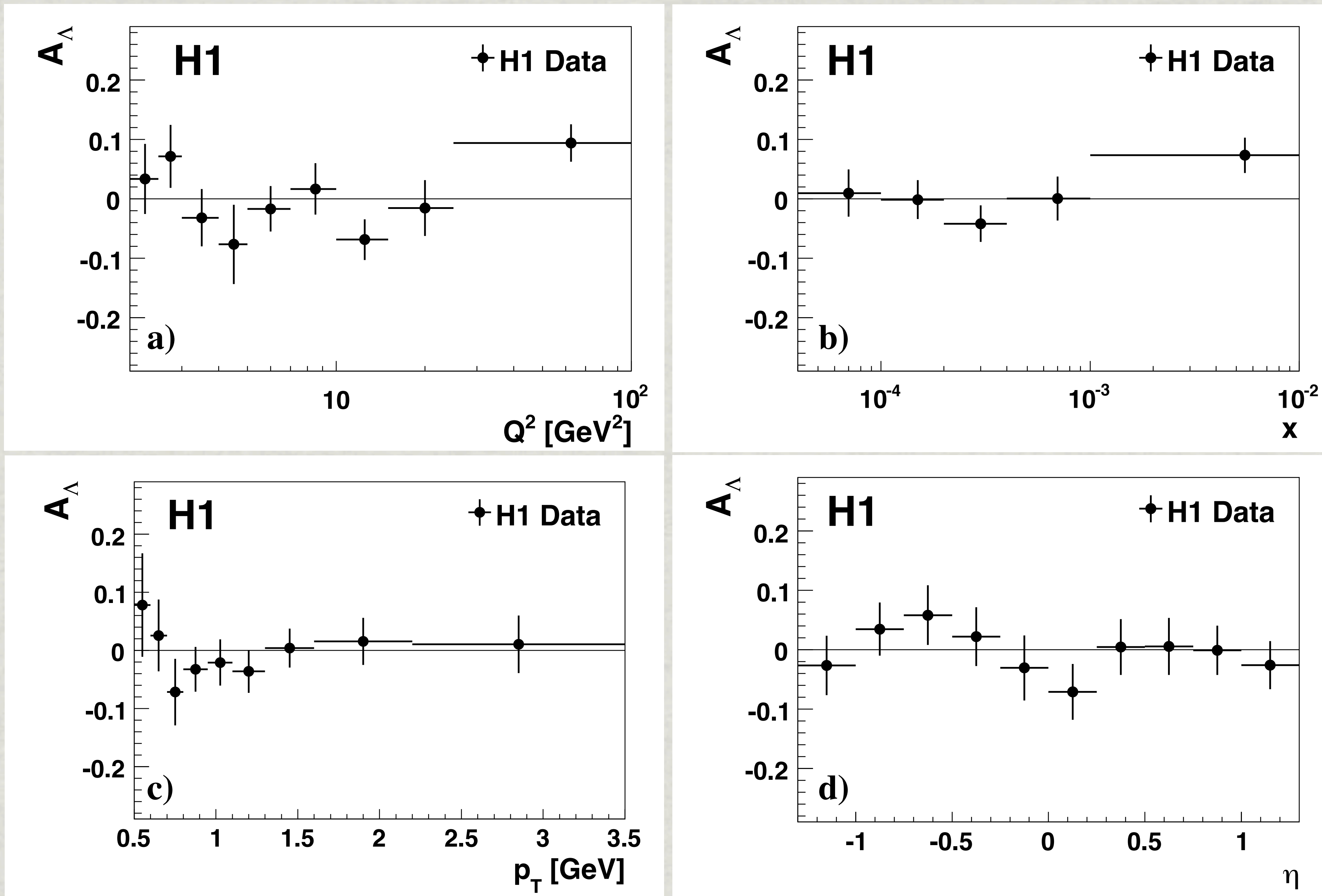




CONSTANT FOR η, Q, X_{BJ}

STRONG DEPENDENCE ON P_T, EXPECTED

Strangeness $\Lambda\bar{\Lambda}$



A SIGNIFICANT ASYMMETRY BETWEEN $\Lambda\bar{\Lambda}$ WOULD INDICATE THAT BARYON NUMBER WAS BEING TRANSFERRED FROM THE PROTON BEAM TO THE FINAL STATE

ALL DISTRIBUTIONS CONSISTENT WITH ZERO - BUT LIMITED ACCEPTANCE

Strangeness in γp

Analysis basics

$\rho^0(770) \rightarrow \pi^+\pi^-$
$\phi(1020) \rightarrow K^+K^-$
$K^{*0}(892) \rightarrow K^{+/-}\pi^{-/+}$

QUASI-REAL PHOTON PROTON INTERACTIONS

TAGGED PHOTOPRODUCTION

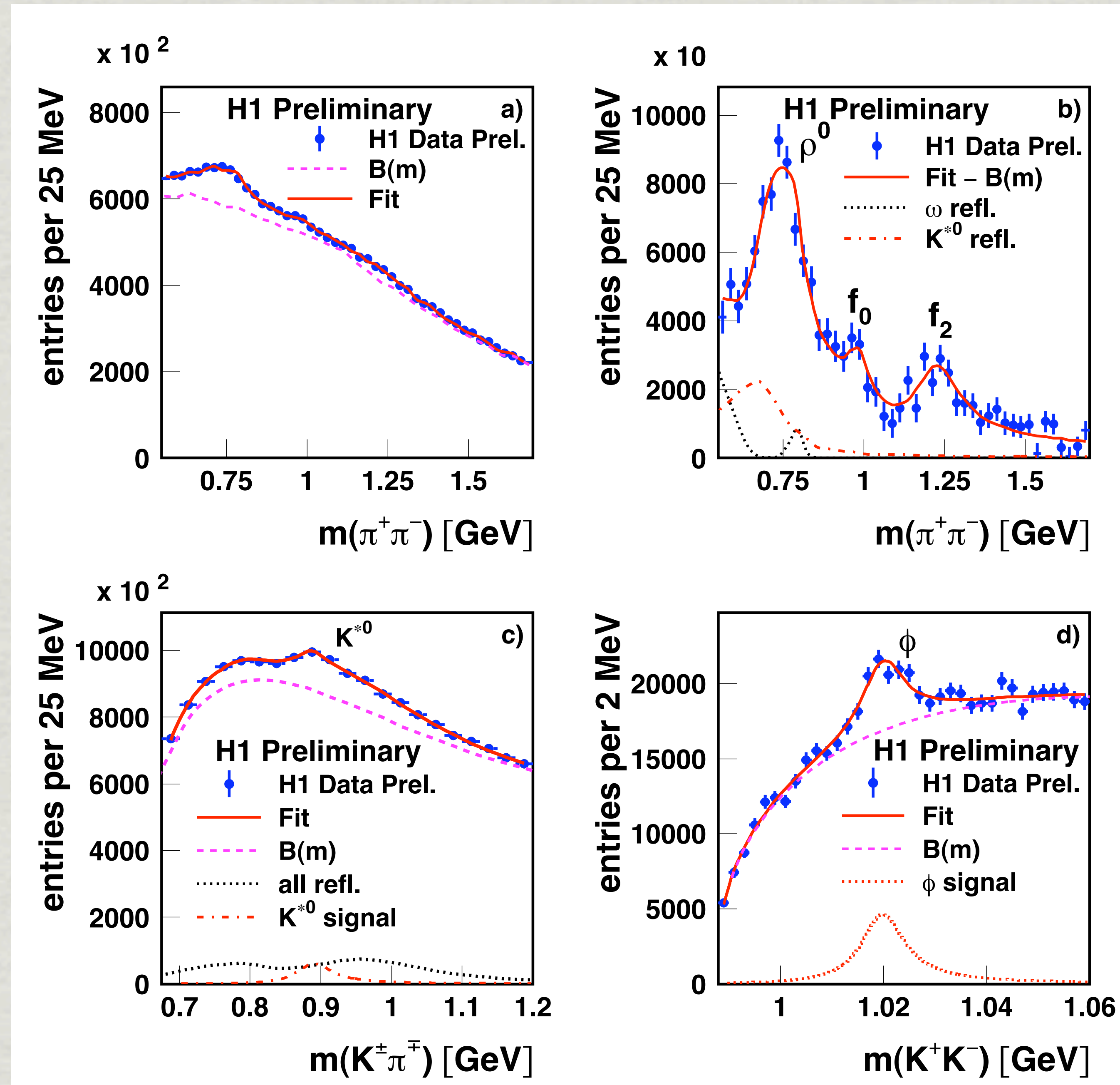
$Q^2 < 0.04\ \mathrm{GeV}^2$

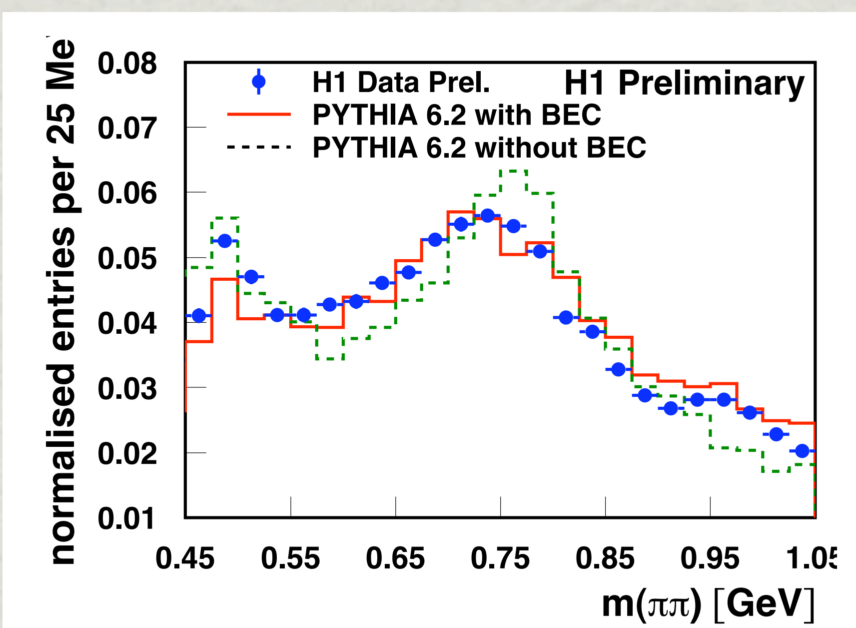
$174 < W < 256$ GeV

$\langle W \rangle = 210$ GeV

$P_{T,\rho^0 K^{*0} \phi} > 0.5$ GeV

$|\eta_{,\rho^0 K^{*0} \phi}| < 1.0$





BOSE-EINSTEIN CORRELATIONS

$$F(m) = B(m) + \Sigma R(m) + \Sigma S(m)$$

RELATIVISTIC BREIT-WIGNER + RESOLUTION FUNCTION

Strangeness in γp

DAMPED POWER LAW

UBIQUITOUS IN NATURE

$$\frac{1}{\pi}\frac{d^2\sigma^{\gamma p}}{dp_T^2 dy} = \frac{A}{(E_{T_0} + E_T^{kin})^n}$$

NORMALISATION FACTOR

TRANSVERSE KINETIC ENERGY

$$E_T^{kin} = \sqrt{m_0^2 + p_T^2} - m_0$$

CLASSICAL THERMODYNAMIC ANALOGY, BOLTZMANN LIKE EXPONENTIAL

$$exp(-E_T^{kin}/T)$$

$E_T^{kin} small$

$$T = E_{T_0}/n$$

TEMPERATURE AT WHICH HADRONISATION TAKES PLACE

$E_T^{kin} large$

$E_{T_0} = 0$

→ POWER LAW AS EXPECTED FROM QCD

IN pQCD n IS A CONVOLUTION OF PARTON DENSITIES AND PARTON PARTON CROSS SECTIONS

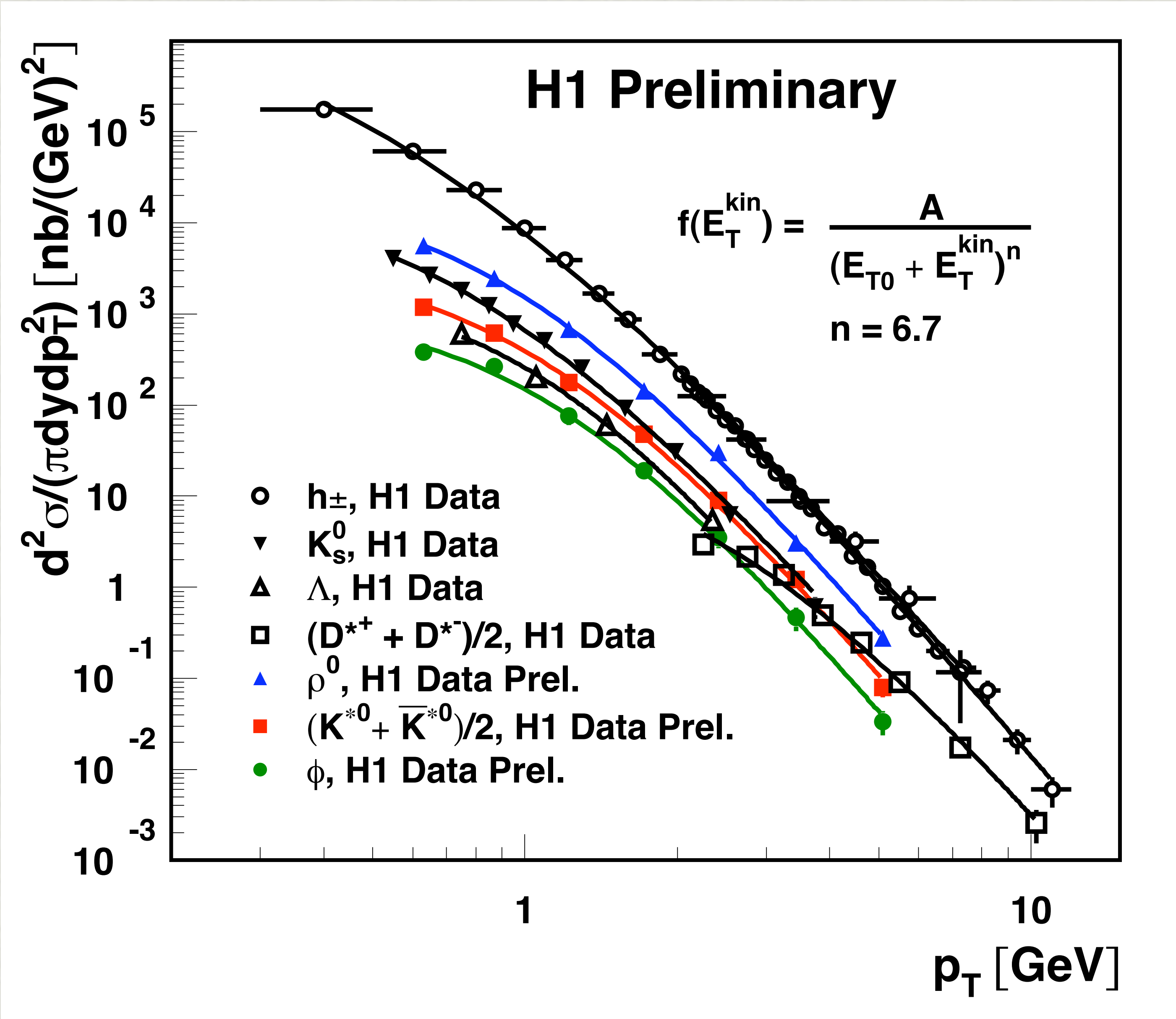
Strangeness in γp

N=6.7 TAKEN FROM PRECISE CHARGED PARTICLE DATA

PARTICLES PRODUCED WITH DIFFERENT MASSES, LIFETIMES AND STRANGENESS CONTENT HAVE SAME AVERAGE TRANSVERSE KINETIC ENERGY

THERMODYNAMIC PICTURE OF HADRONISATION WHERE PRIMARY PARTICLES THERMALISED DURING HADRONISATION

$$< p_t >= \sqrt{< E_T^{kin} >^2 + 2 < E_T^{kin} > m_0}$$



RHIC W = 200 GeV

	ρ^0	K^{*0}	φ
$<p_t>_{\gamma p}$	0.726 ± 0.021	0.811 ± 0.025	0.860 ± 0.032
$<p_t>_{pp}$	0.616 ± 0.062	0.81 ± 0.14	0.82 ± 0.03
$<p_t>_{AuAu}$	0.83 ± 0.1	1.08 ± 0.14	0.97 ± 0.02

	ρ^0	K^{*0}	φ
$T_{\gamma p}$	0.151±0.006	0.166±0.008	0.170±0.009
T_{Pythia}	0.136	0.14	0.149

Strangeness in γp

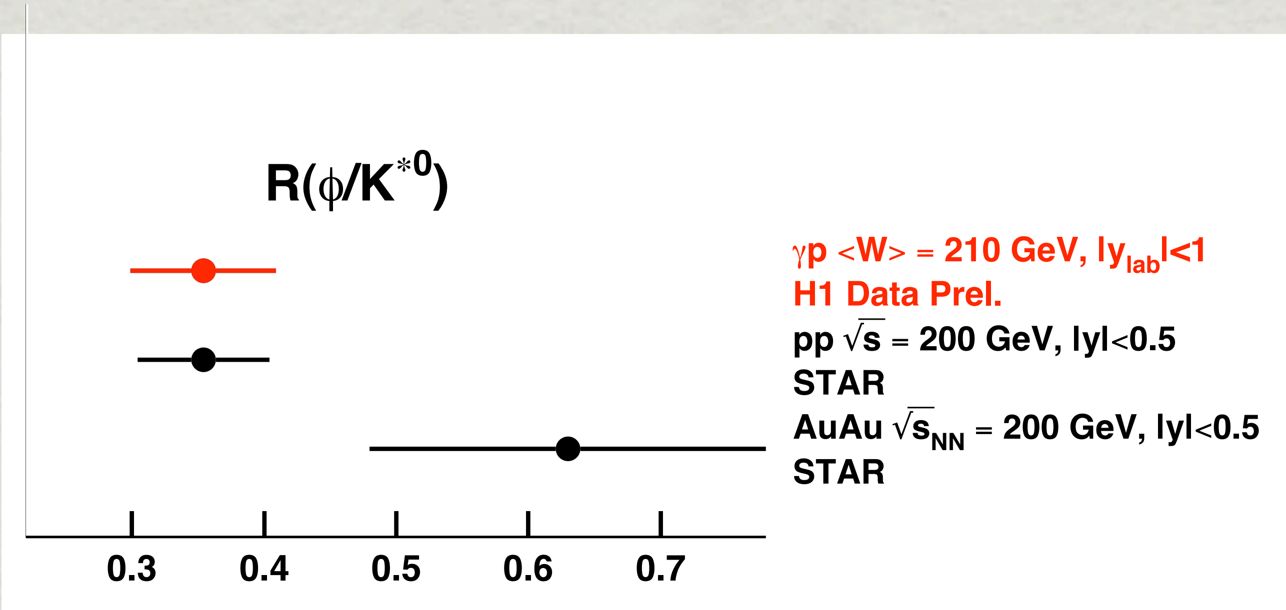
CROSS SECTION RATIOS

INTEGRATED OVER p_t AND y

$R(K^{*0}/\rho^0) = 0.221 \pm 0.033$

$R(\phi/\rho^0) = 0.078 \pm 0.012$

$R(\phi/K^{*0}) = 0.354 \pm 0.055$



ENHANCED PRODUCTION OF ss QUARKONIUM STATE IN *AuAu* COMPARED TO pp AND γp.

PYTHIA / PHOJET MONTE CARLOS NEED $\lambda_s \sim 0.32$ TO DESCRIBE THESE RATIOS

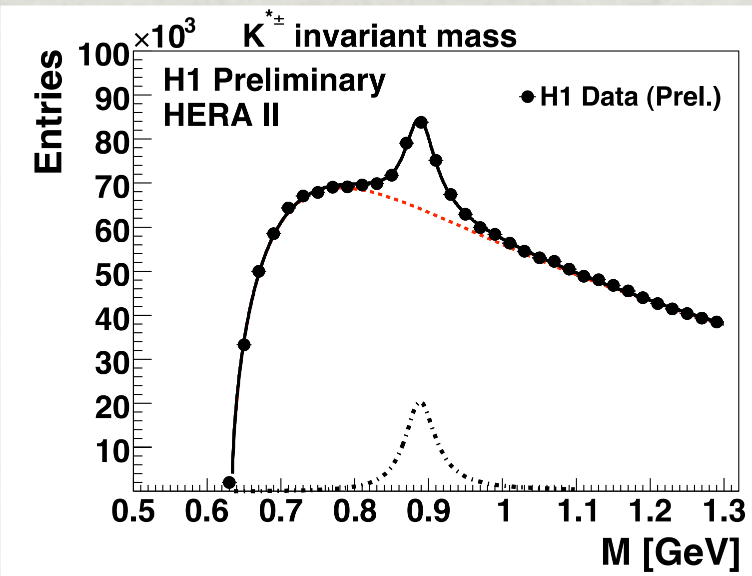
INCONSISTENT WITH DIS RESULTS

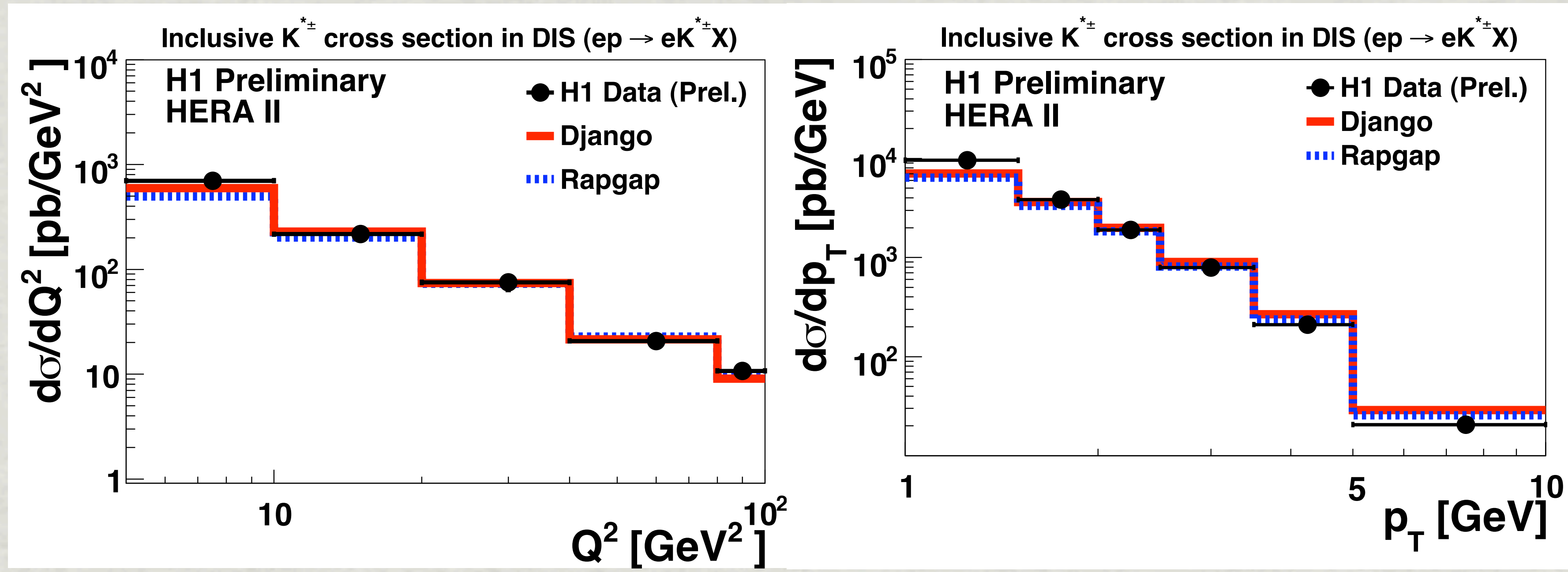
Bonus

$K^{*\pm}$ Production

$5 < Q^2 < 100$ GeV^2

$$K^{*\pm} \rightarrow K^0_s \pi^\pm$$



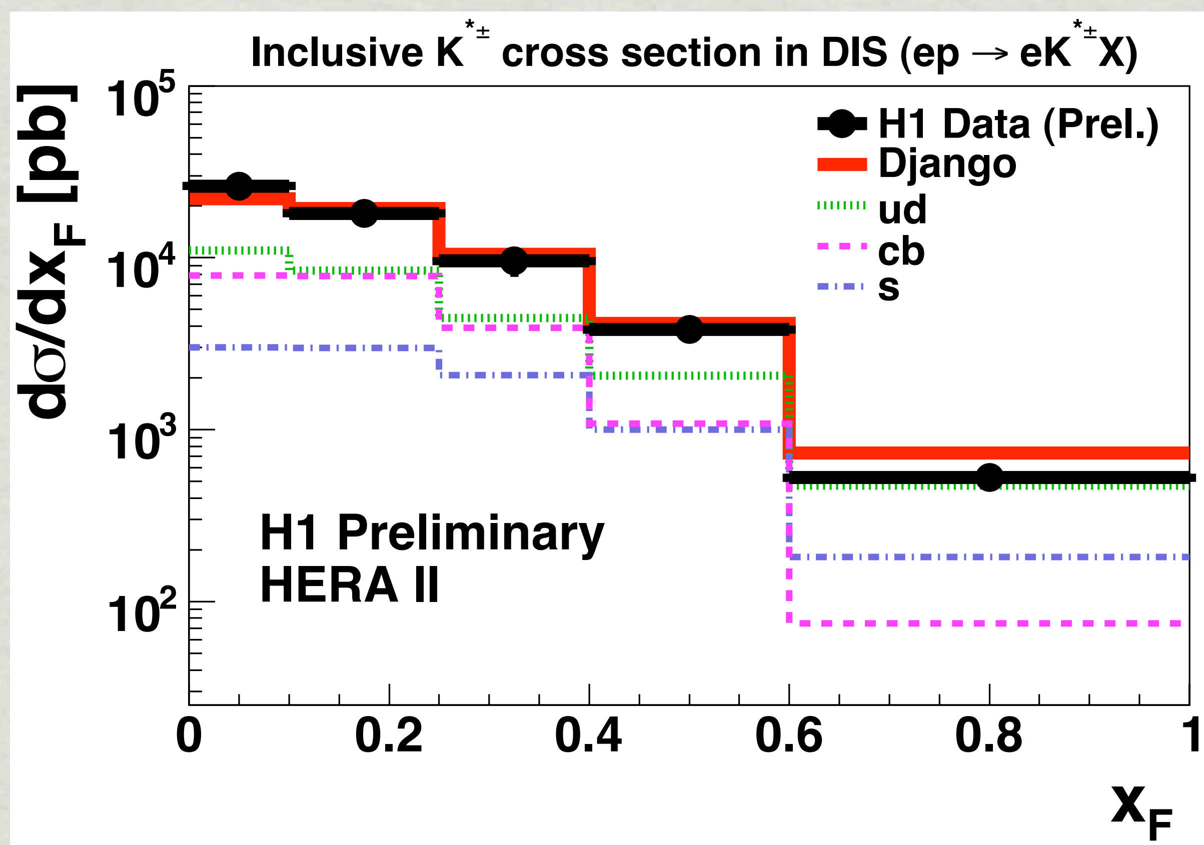


BASIC FEATURES DESCRIBED BY MONTE CARLO MODELS

USE CHARGE TO MEASURE s AND $\bar{s}$ RATE, POSSIBLE SENSITIVITY TO STRANGENESS ASYMMETRY IN PROTON

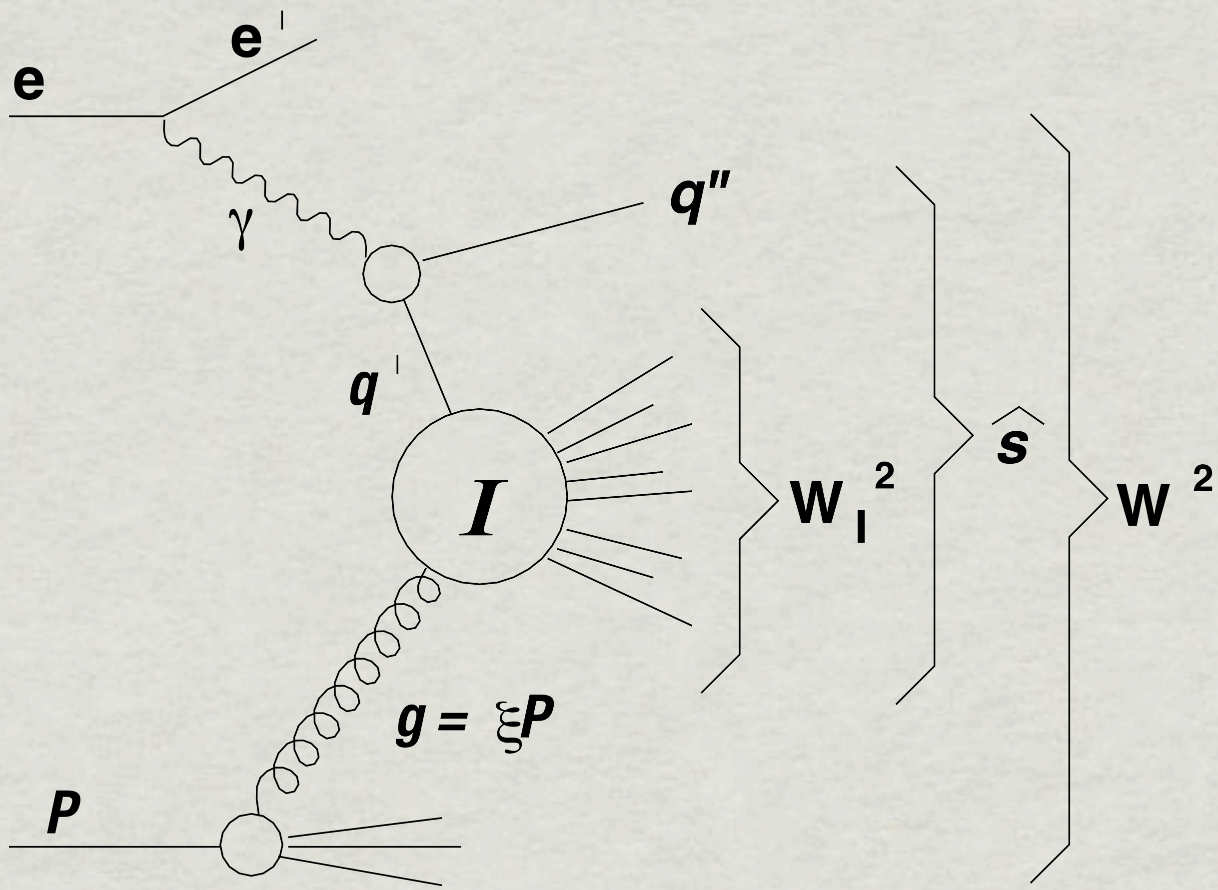
$$x_F = 2P_L/W$$

HADRONIC CENTRE OF MASS FRAME

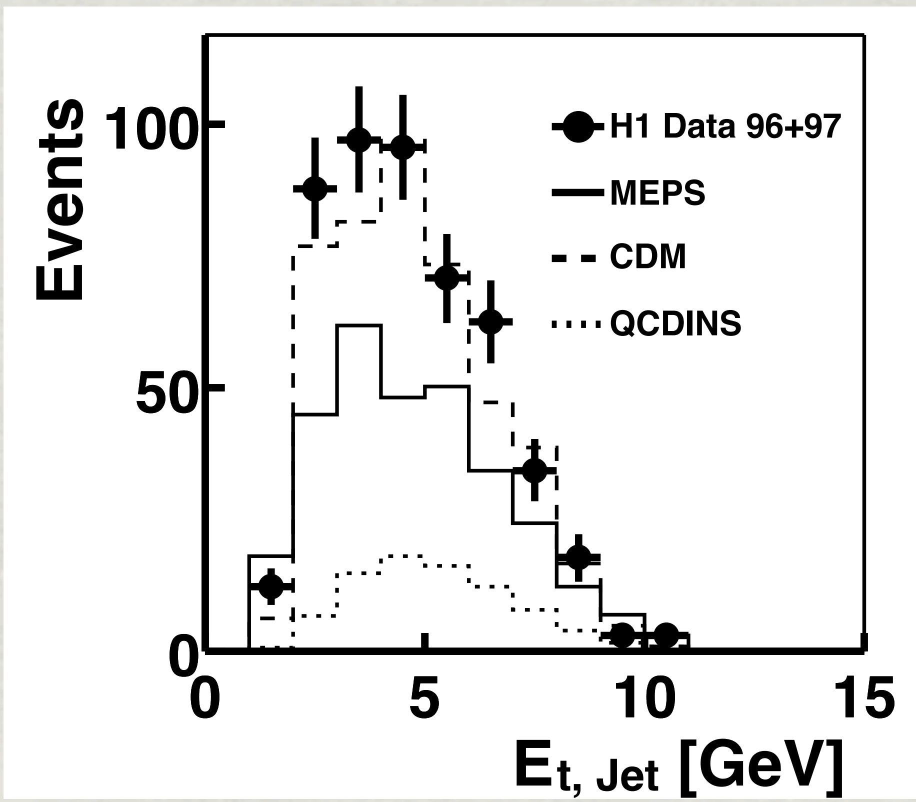


NON STRANGENESS DOMINATES HARD INTERACTION

INSTANTONS ARE NON-PERTURBATIVE FLUCTUATIONS OF THE GLUON FIELD. THEY REPRESENT TUNNELLING TRANSITIONS BETWEEN TOPOLOGICALLY NON-EQUIVALENT VACUA.



THEY ARE REQUIRED BY QCD AND THEIR CROSS SECTION CAN BE CALCULATED, UNDER CERTAIN ASSUMPTIONS, IN QCD



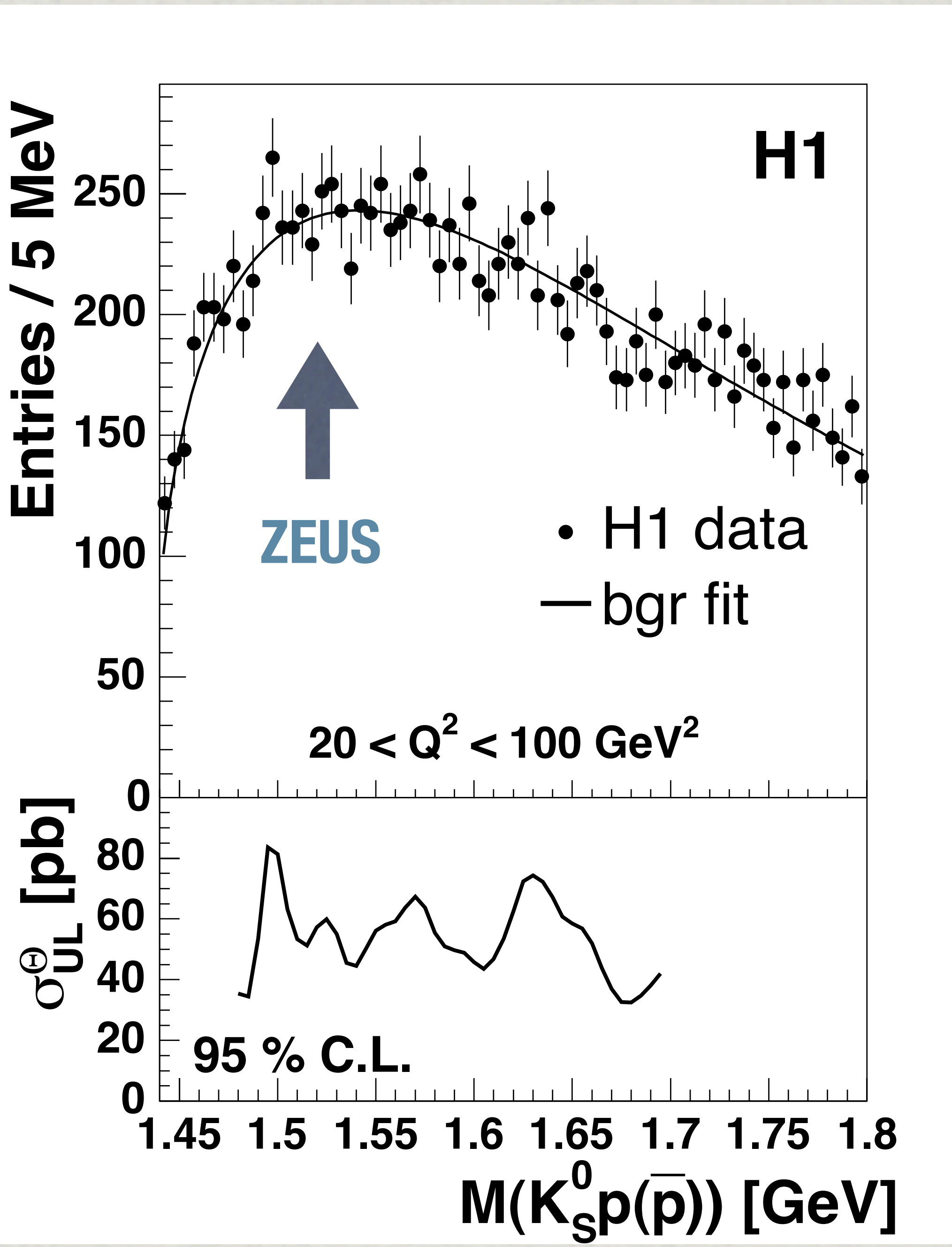
SIGNATURE- A LARGE NUMBER OF HADRONS AT HIGH TRANSVERSE ENERGY EMERGING FROM A “FIRE-BALL” LIKE TOPOLOGY.

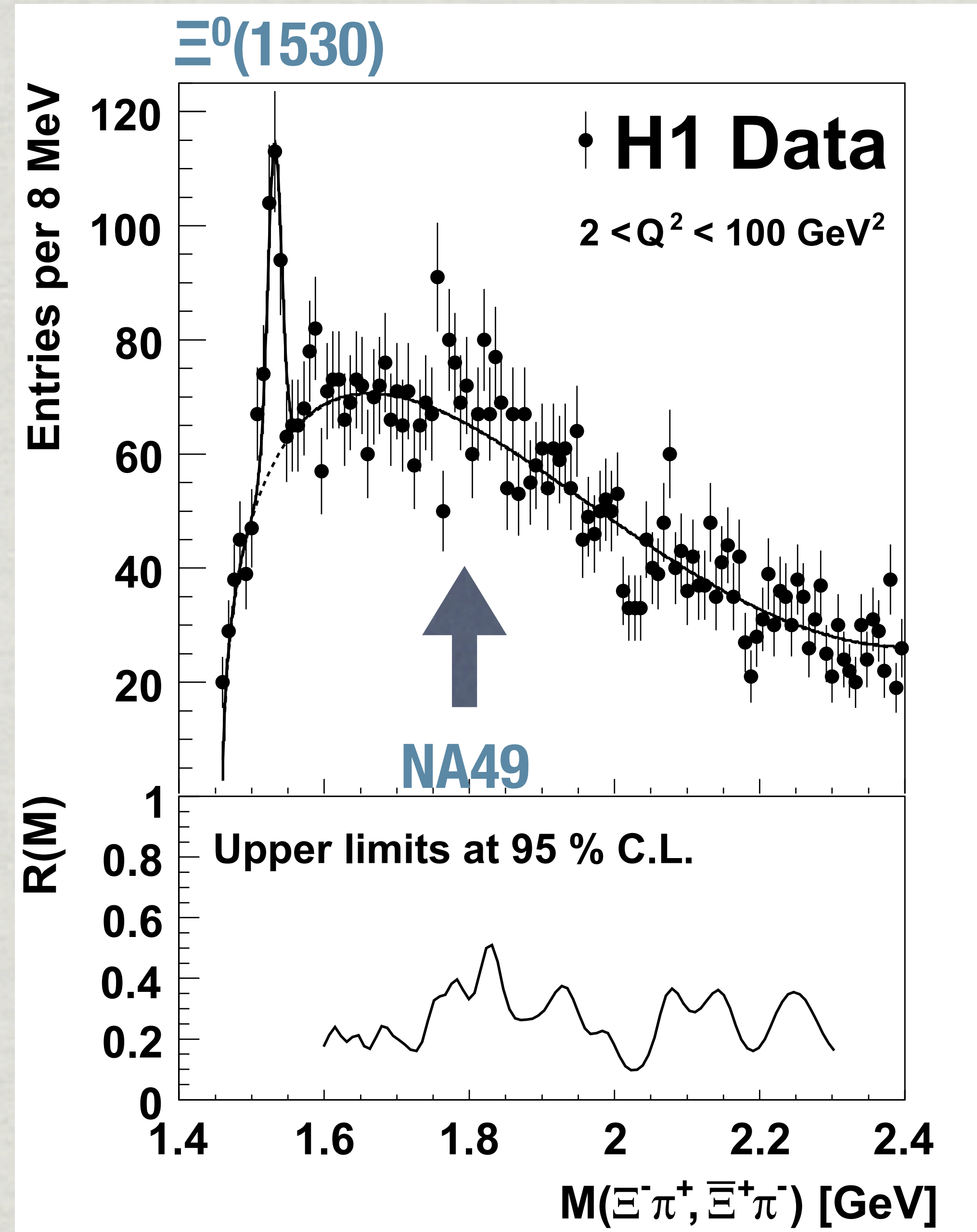
DIFFERENCES IN BACKGROUND PREDICTION LARGER THAN INSTANTONS CROSS SECTION

Pentaquarks

5 QUARK BOUND STATES

MOST RECENT ANALYSES AROUND THE WORLD HAVE PROVED NEGATIVE





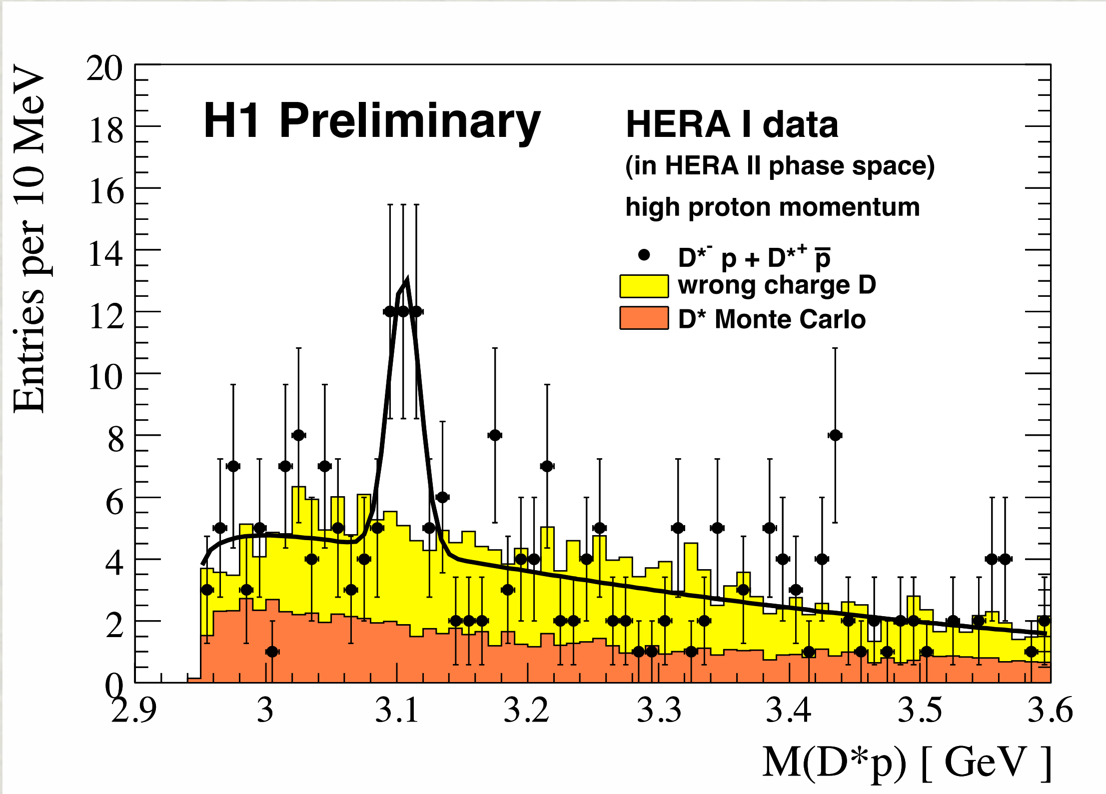
(suuud) $\Theta^+ \rightarrow K^0_s p$

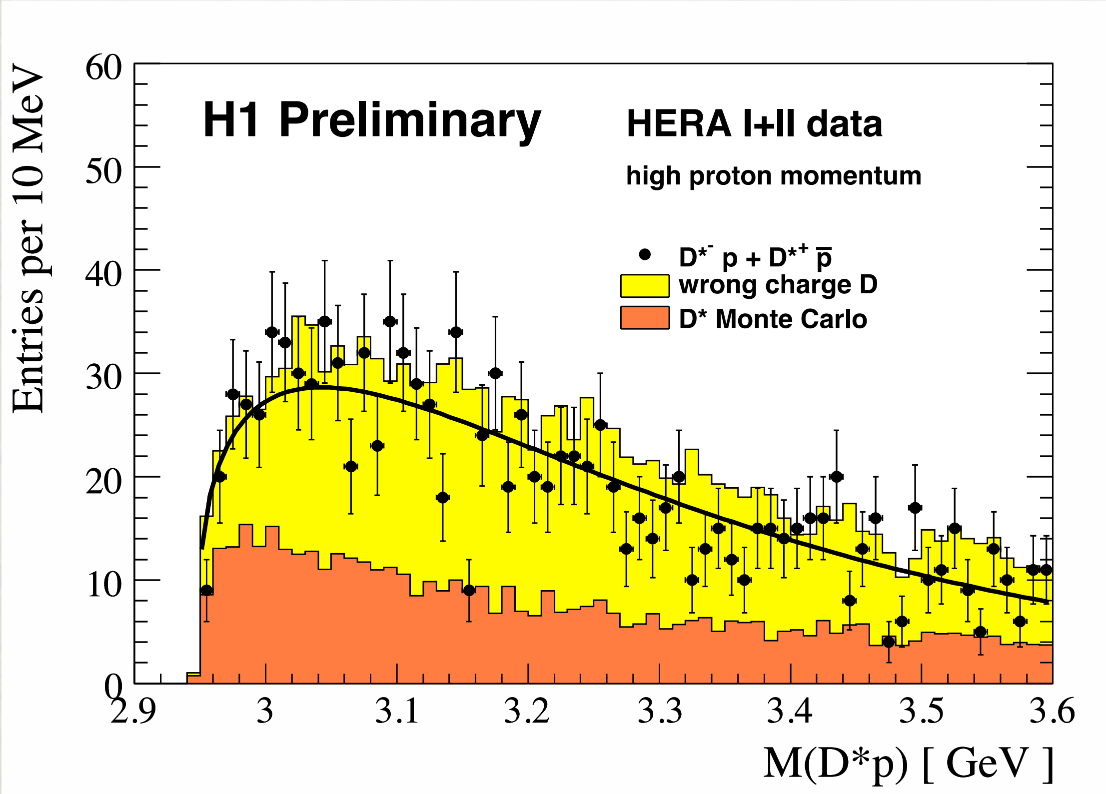
(uussd) $\Xi^0_{5q} \rightarrow \Xi^- \pi^+ \rightarrow [\Lambda \pi^-] \pi^+$

Charmed Pentaquarks

H1 OBSERVED SIGNAL FOR A CHARMED PENTAQUARK IN HERAI DATA SET

NO SIGNAL OBSERVED IN HERAII !

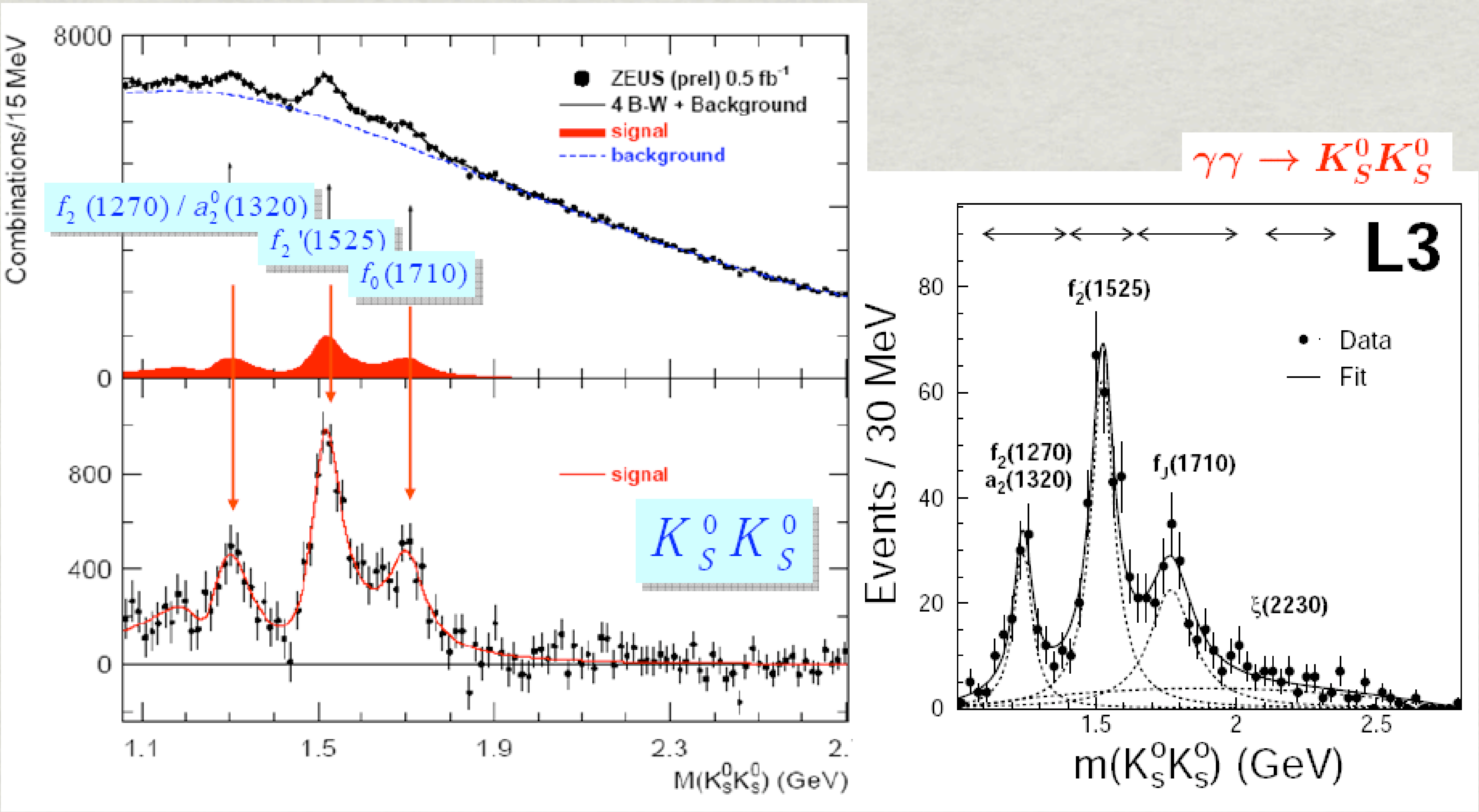




OTHER EXPERIMENTS LOOKED FOR IT BUT FAILED TO SEE ANYTHING

Glueballs

K0K0 FINAL STATES



INTERFERENCE EFFECTS INCLUDED IN FIT

K0K0 SYSTEM EXPECTED TO COUPLE TO SCALAR AND TENSOR GLUEBALLS, F01720 GLUEBALL CANDIDATE FROM LATTICE CALCULATIONS.

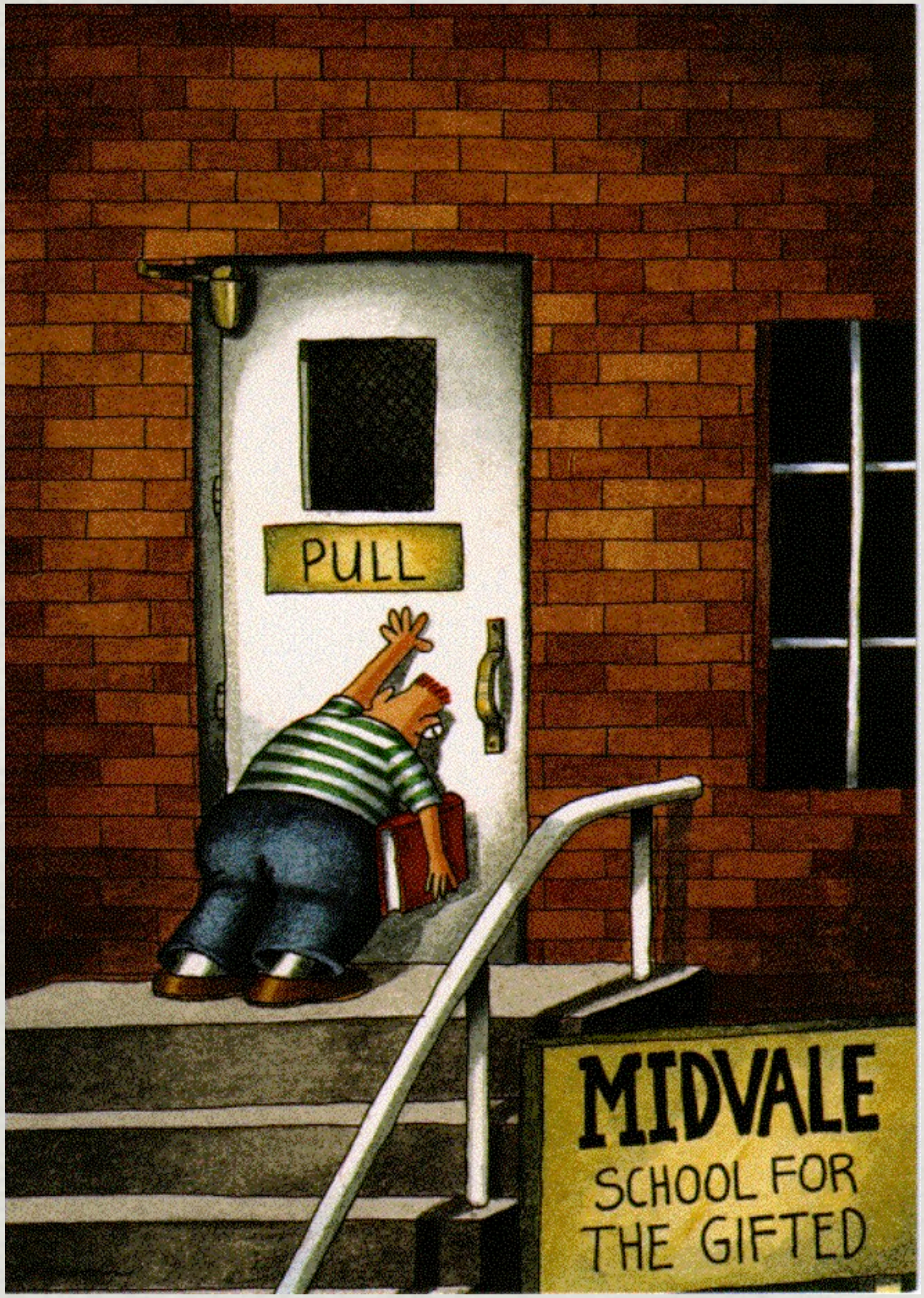
f0(1710) CANNOT BE A PURE GLUEBALL, SINCE IT COUPLES TO γγ. MUST THEREFORE MIX

Summary

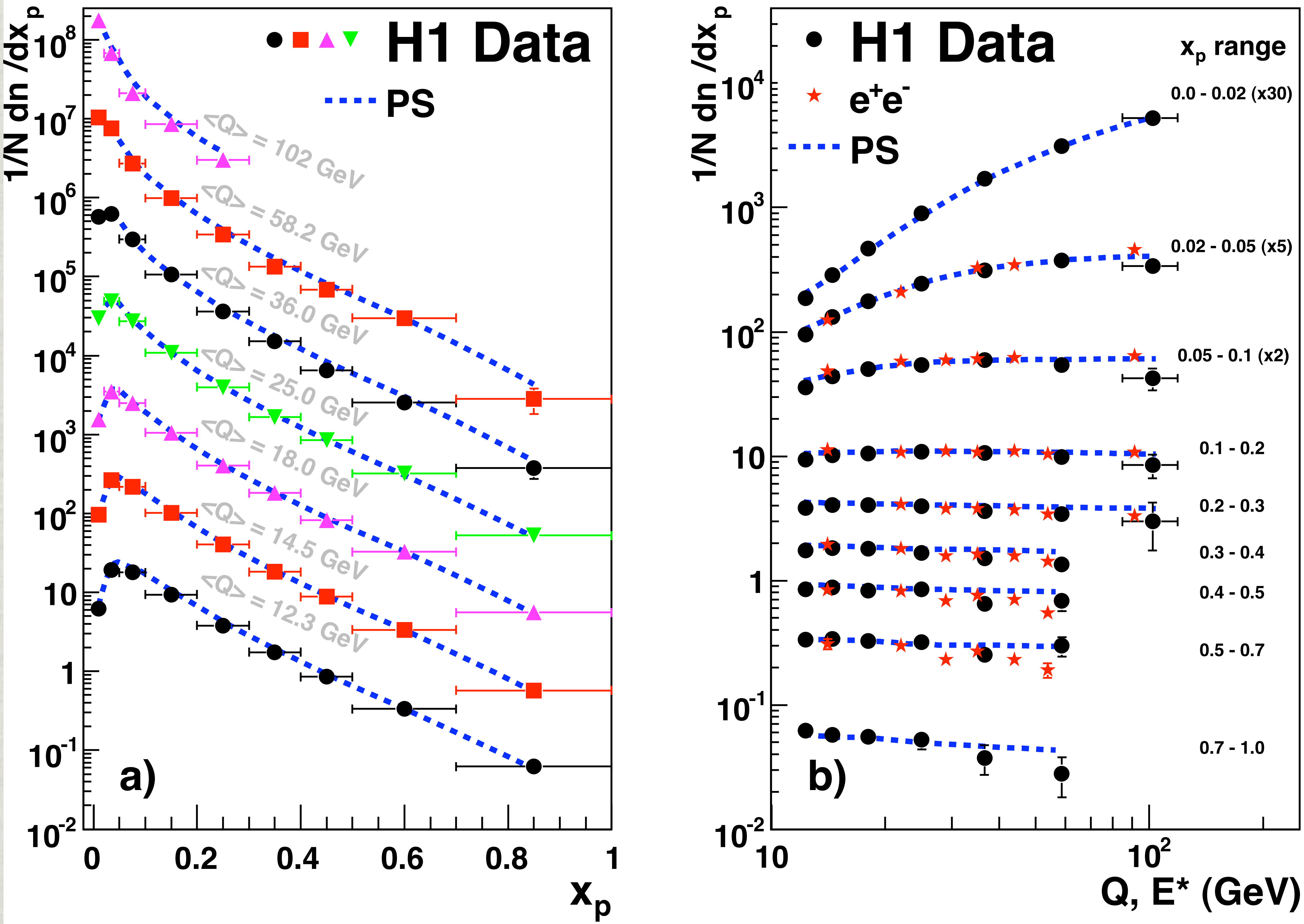
- With HERA data there is the possibility to study many different aspects of (np)QCD via particle production.
- Universality of fragmentation broadly supported BUT there are differences in detail when comparing to models (NLO FF, λ_s, string length etc...).
- Expect further results on strangeness, instantons, underlying event, multi parton dynamics.

Summary

QCD IS CLEVER BUTS ITS NOT THAT CLEVER

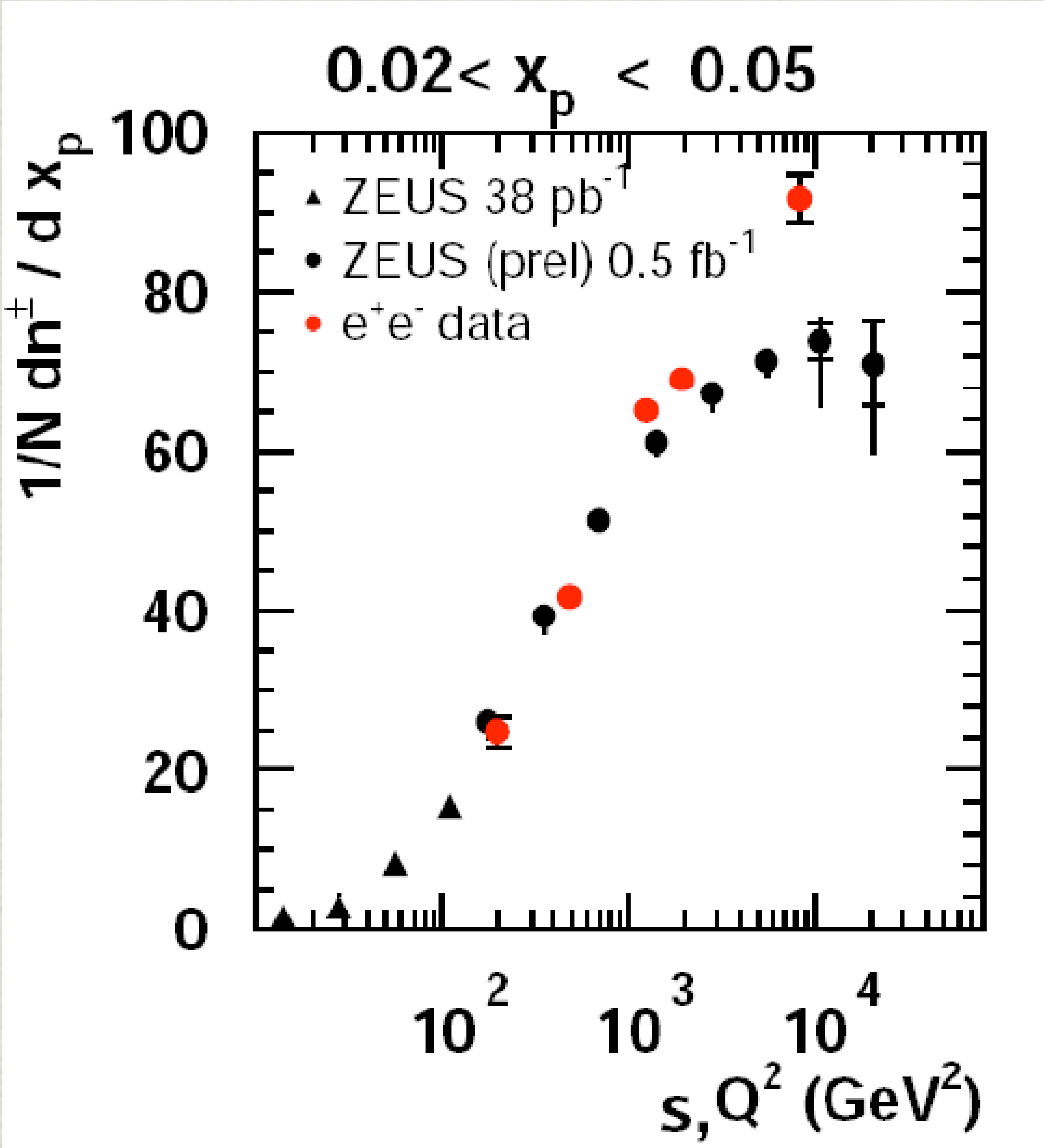


backup



1/N dn /dx_p
H1 Data
PS
<Q> = 102 GeV
<Q> = 58.2 GeV
<Q> = 36.0 GeV
<Q> = 25.0 GeV
<Q> = 18.0 GeV
<Q> = 14.5 GeV
<Q> = 12.3 GeV
a)
x_p
1/N dn /dx_p
H1 Data
e+e-
PS
x_p range
0.0 - 0.02 (x30)
0.02 - 0.05 (x5)
0.05 - 0.1 (x2)
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.7
0.7 - 1.0
b)
Q, E* (GeV)

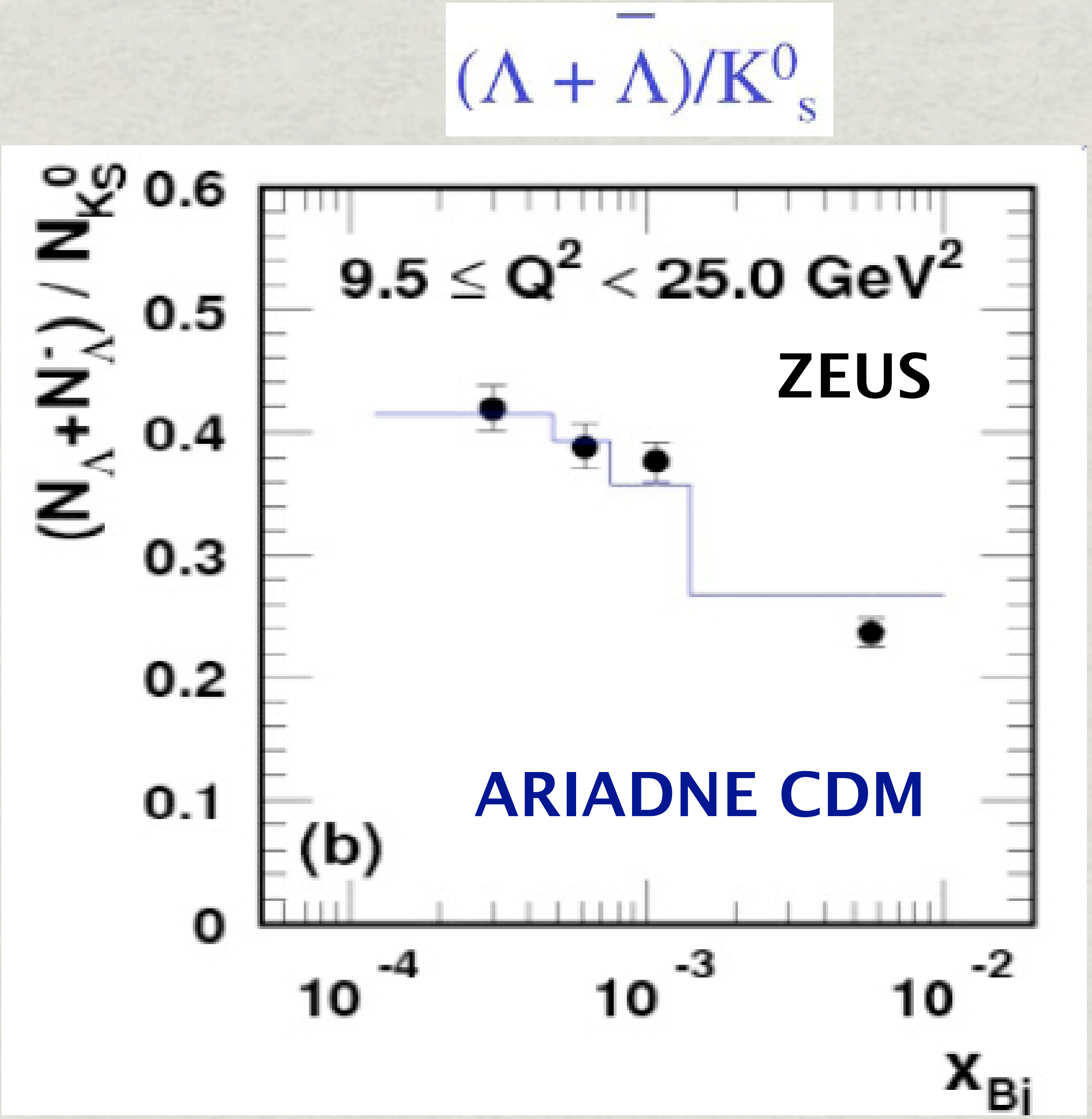
one x_p bin in detail

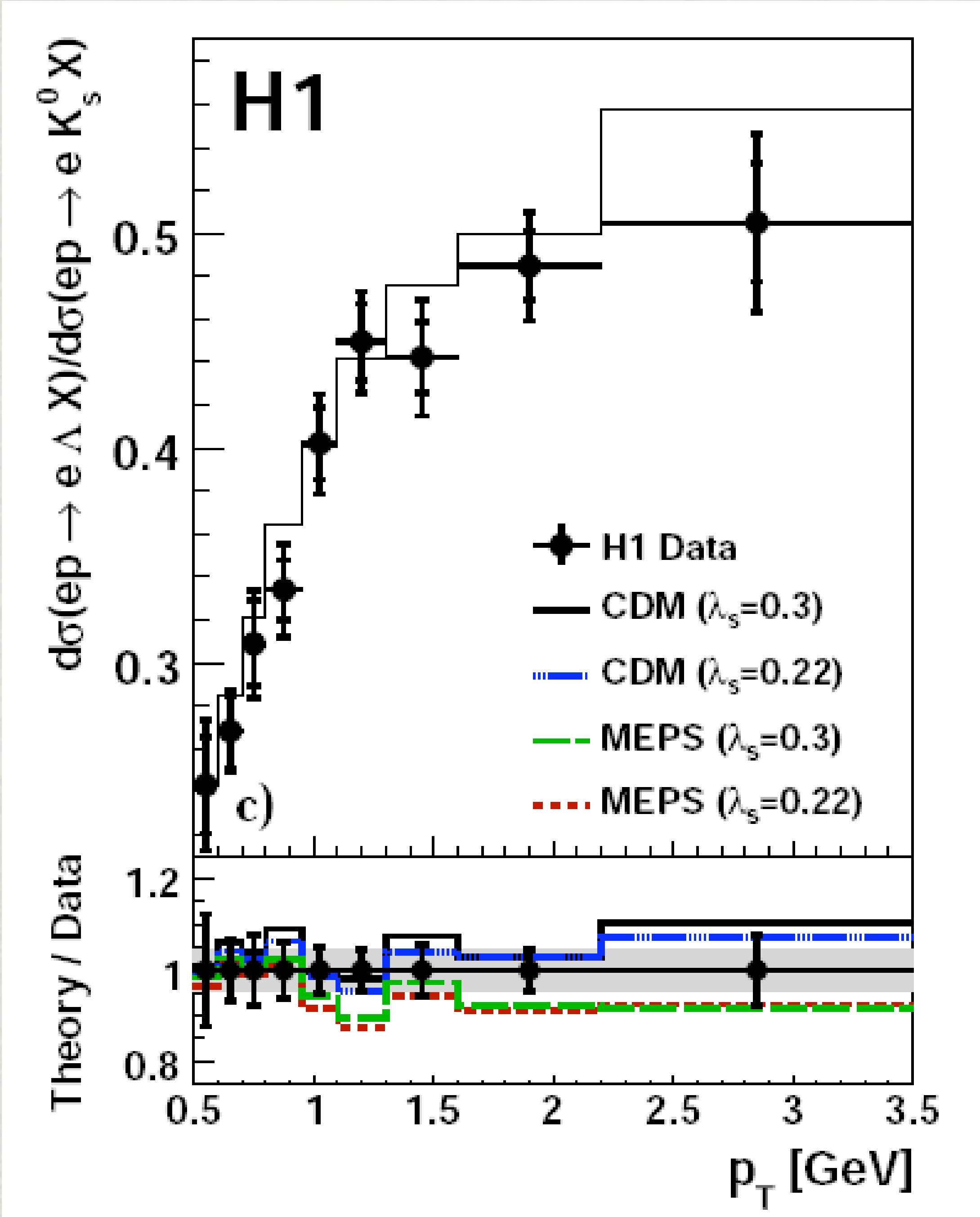


Strong scaling violation at this low x_p.

Deviation between e^+e^- and ep at highest s or Q^2.

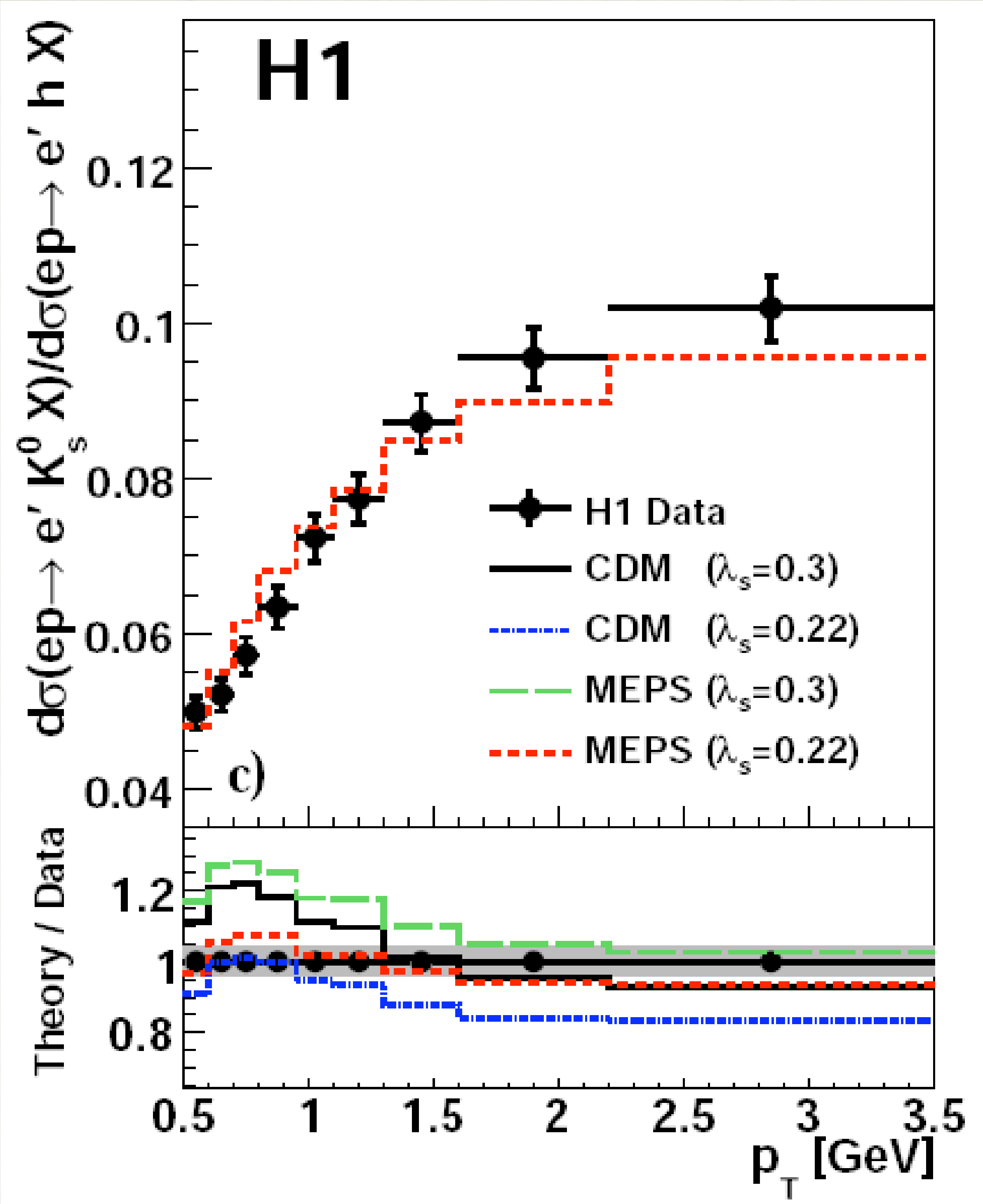
Strangeness production ratio





Color dipole model with λ_s = 0.3 gives best description (not perfect).

K^0 to charged hadron ratio



Ratio K^0/h has less sensitivity to PDFs and hard scattering process. Enhanced sensitivity to details of strangeness production.

Ratio K/hadrons best described by MEPS with smaller λ_s = 0.22.

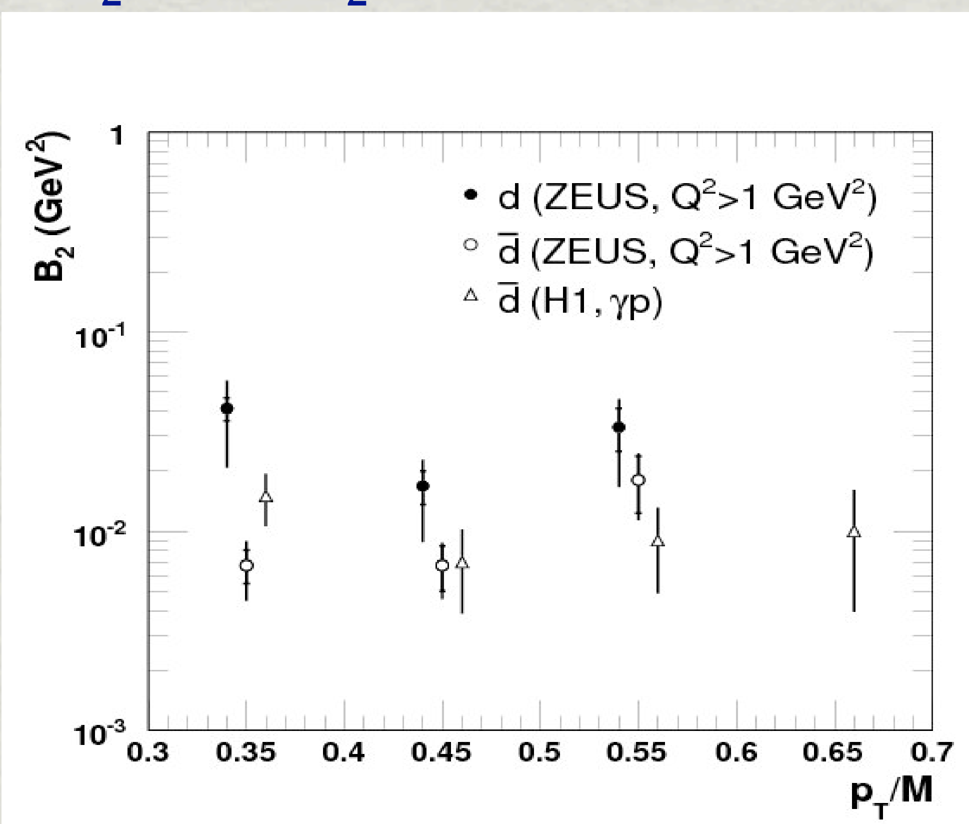
No single combination of model and λ_s describes all data.

Deuteron production

Coalescence model:

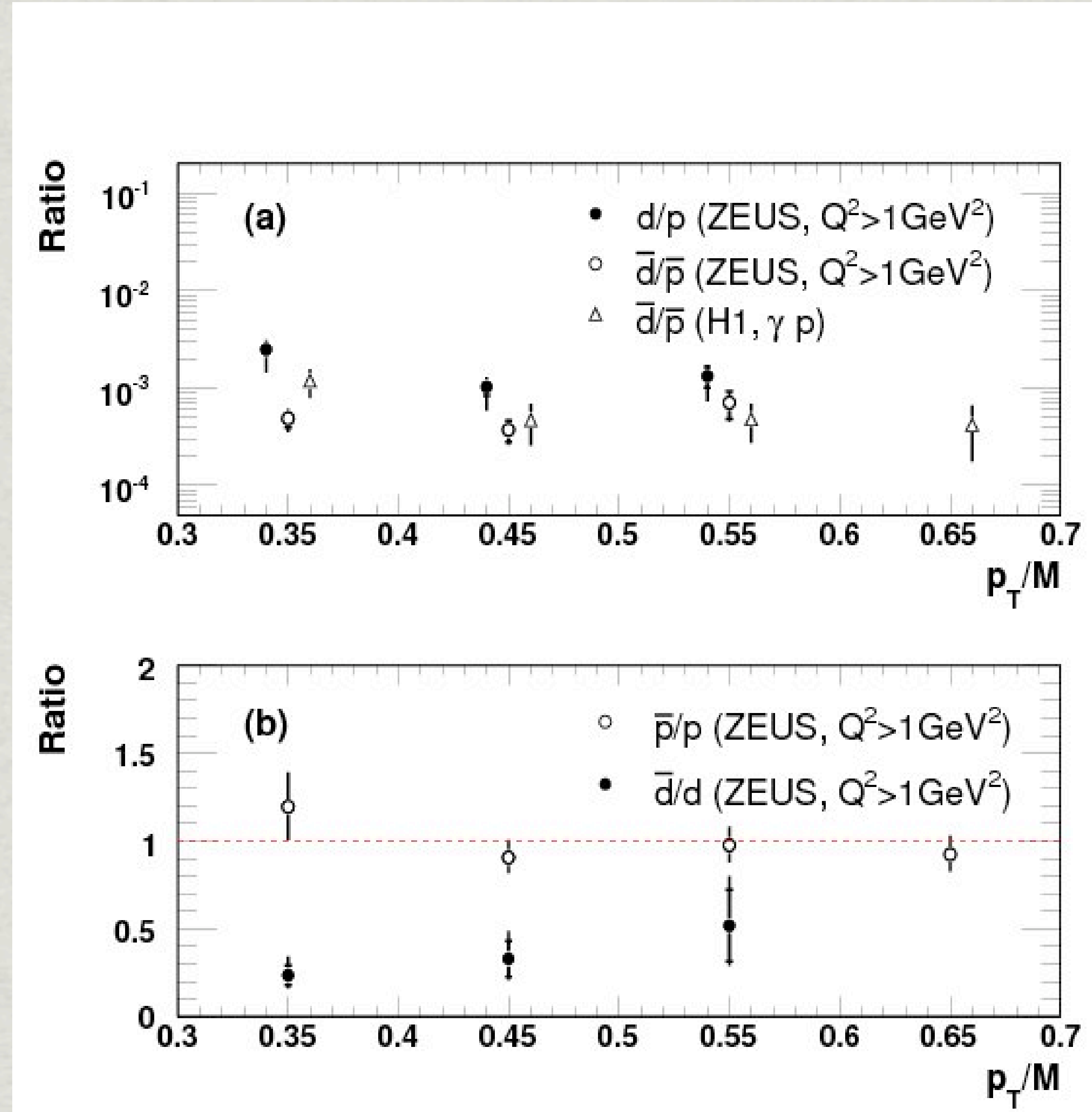
$$\frac{1}{\sigma}\frac{d^3\sigma(d)}{d^3p} = B_2\left(\frac{1}{\sigma}\frac{d^3\sigma(p)}{d^3p}\right)\left(\frac{1}{\sigma}\frac{d^3\sigma(n)}{d^3p}\right)$$

$B_2(d) = B_2(\bar{d})$ is expected



$$B_2(d) = 3.32 \pm 0.34^{+1.13}_{-1.55}$$

$$B_2(\bar{d}) = 0.89 \pm 0.14^{+0.19}_{-0.20}$$



Enhanced production of multi-quark states?