Beyond the Standard Model searches at HERA

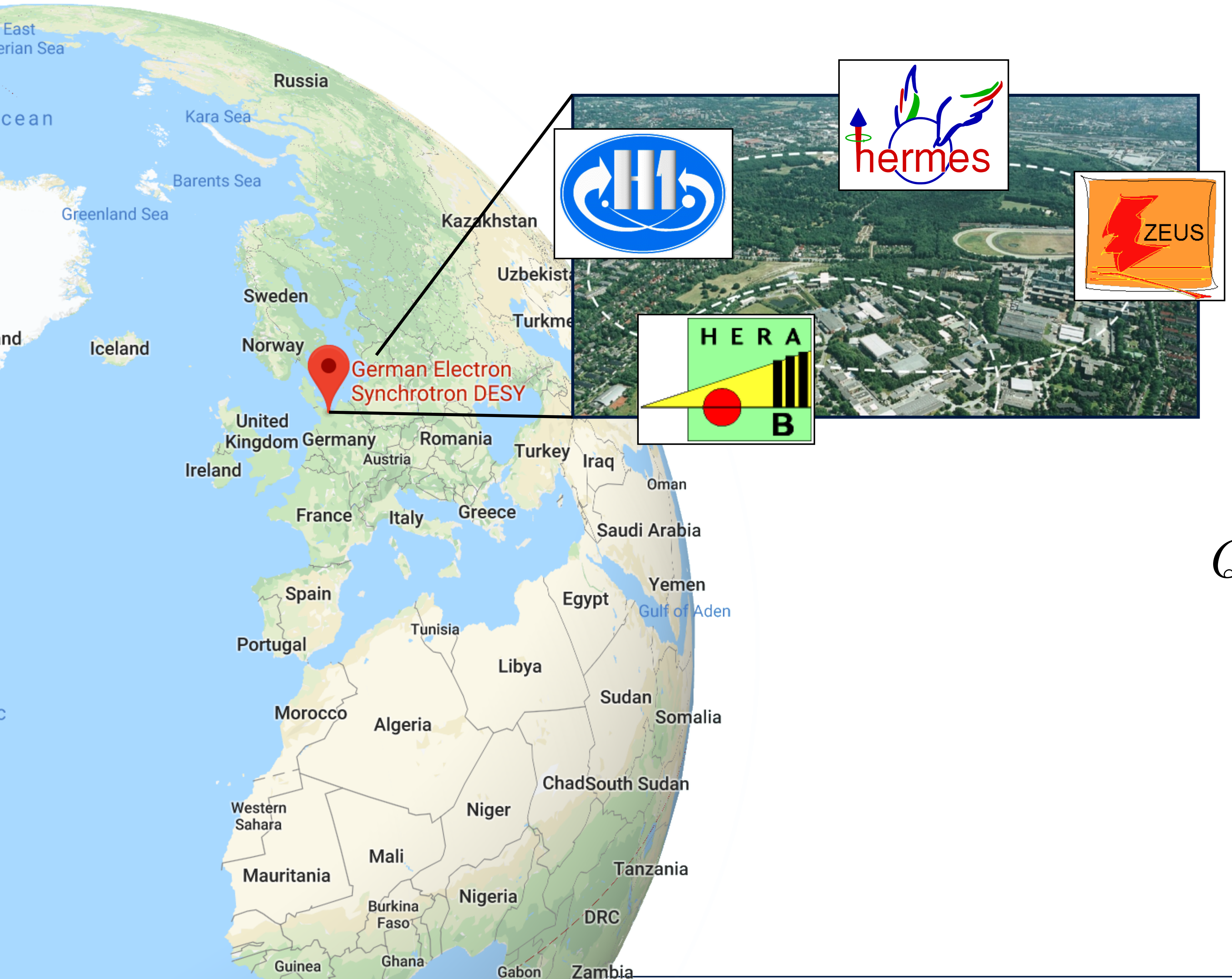
LP 2019

O. Turkot
On behalf of H1 and ZEUS Collaborations

- Pentaquarks searches
- Isolated and multi- leptons
- General contact interactions and leptoquarks
- BSM weak couplings

6 August 2019

HERA - world's only high energy $e^{\pm}p$ collider



HERA operated during 1992 - 2007 with:

> ***e***$^{\pm}$ energy of 27.5 GeV;
> ***p*** energies of 920, 820, 575 and 460 GeV.

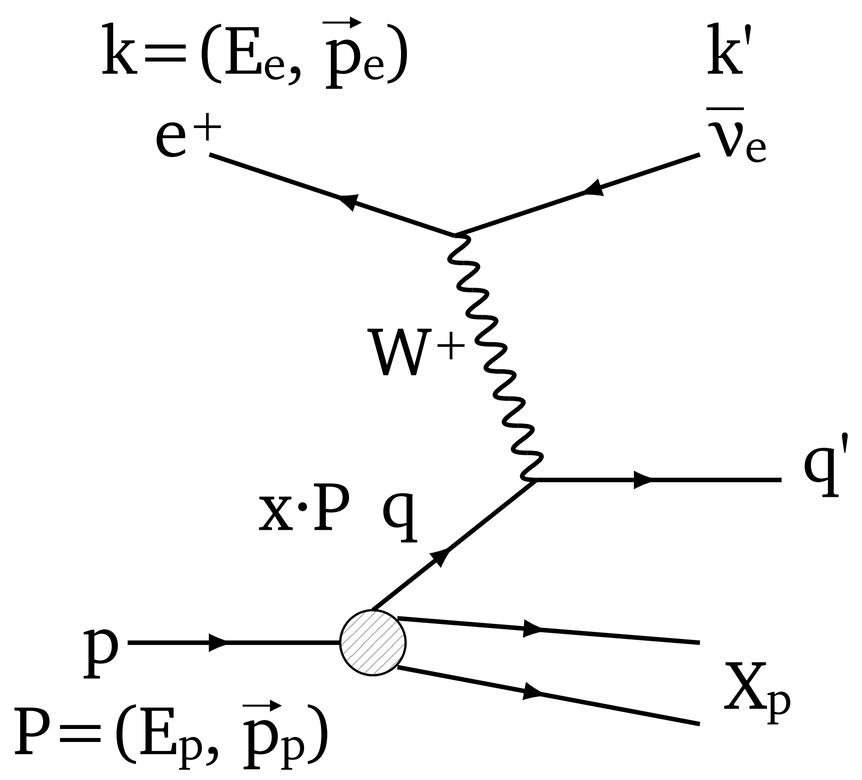
H1 and **ZEUS** - two general purpose collider experiments at HERA:

> **~0.5 fb^{-1}** of luminosity were recorded by each experiment.

$$Q^2 = -(k - k')^2$$

$$x_{Bj} = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$



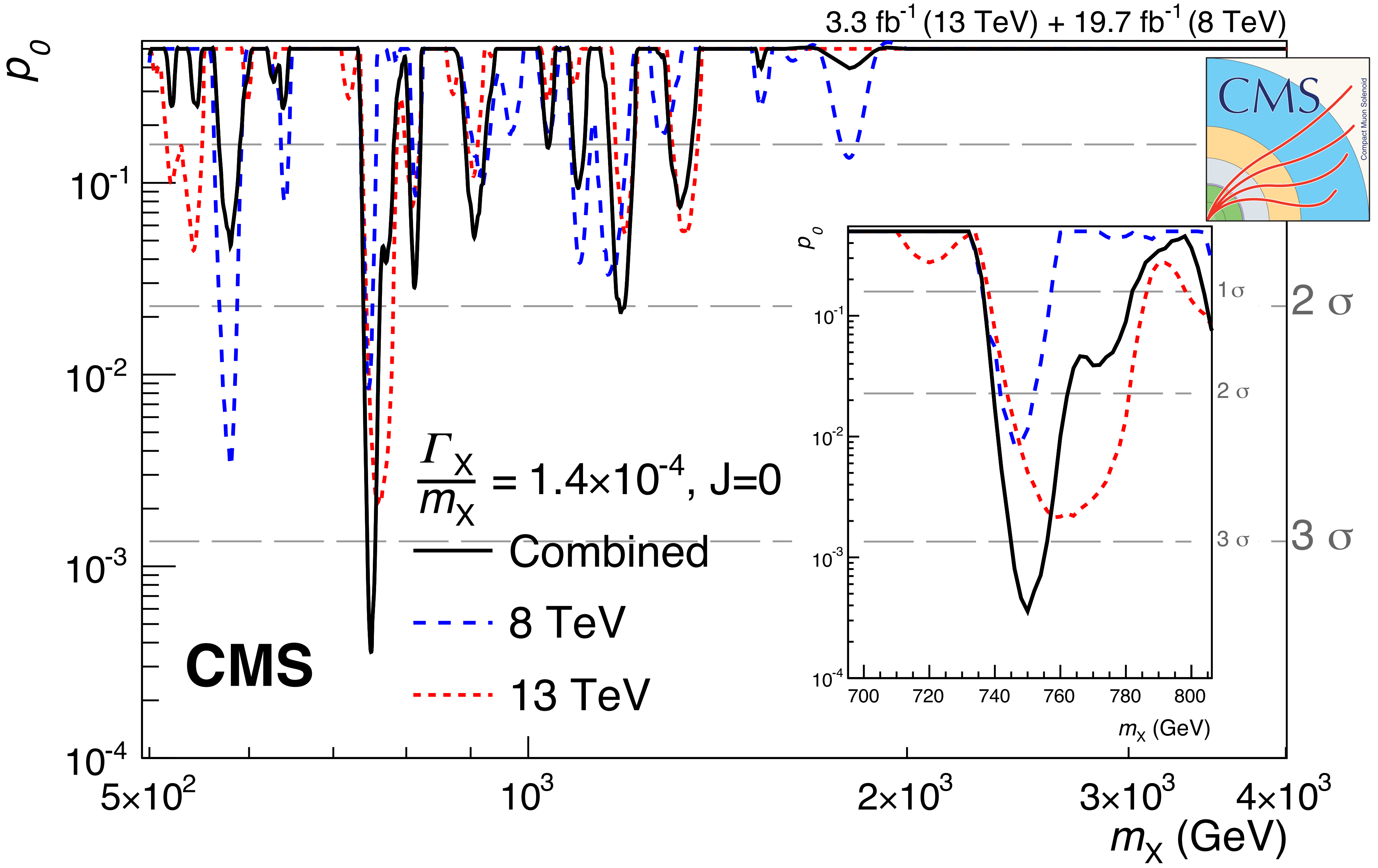
2015 - early 2016:

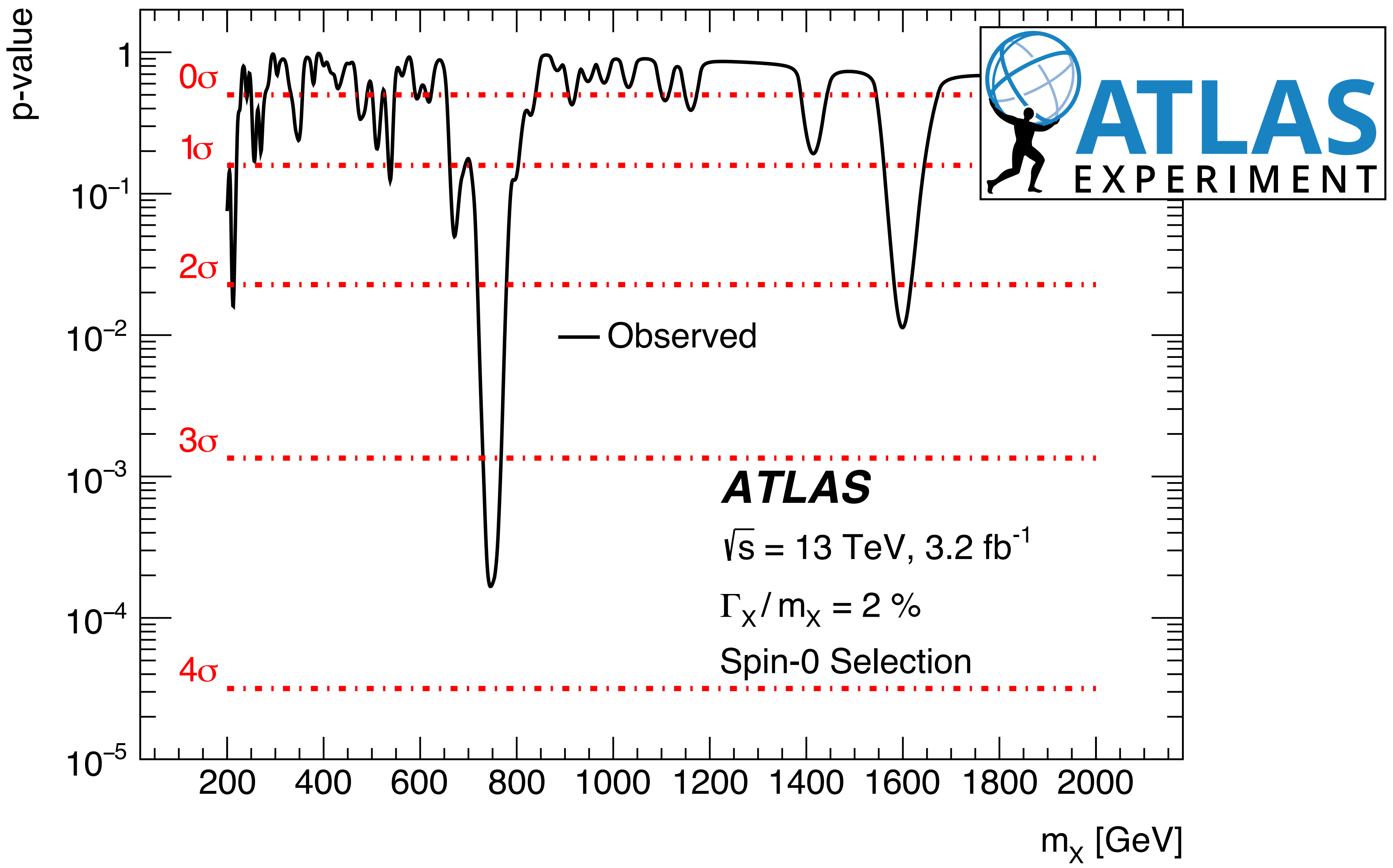
~3.5 σ excess of the di-photon events for the resonance mass:

$$m_X = 750 \sim 760 \text{ GeV}$$

observed in both, **Atlas** and **CMS**, experiments.

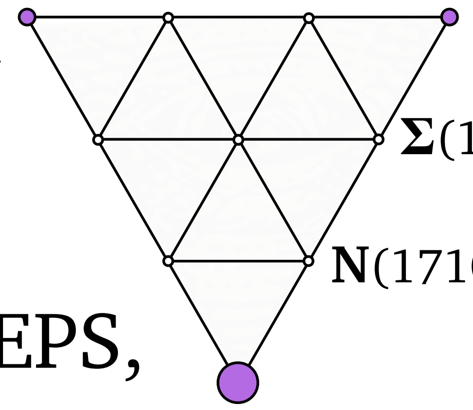
~600 theory papers.





2003 - 2004:

~4 σ evidence at CERN SPS

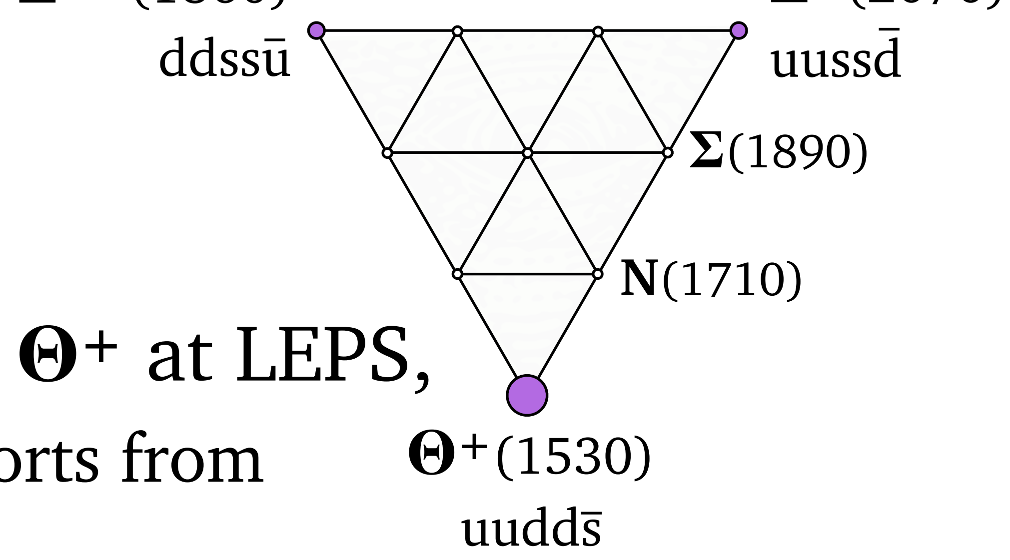


~4.5 σ evidence of Θ^+ at LEPS,
followed by ~4 σ reports from
9 more experiments

2003 - 2004:

~4 σ evidence at CERN SPS

[Z. Phys. A 359 (1997) 305]



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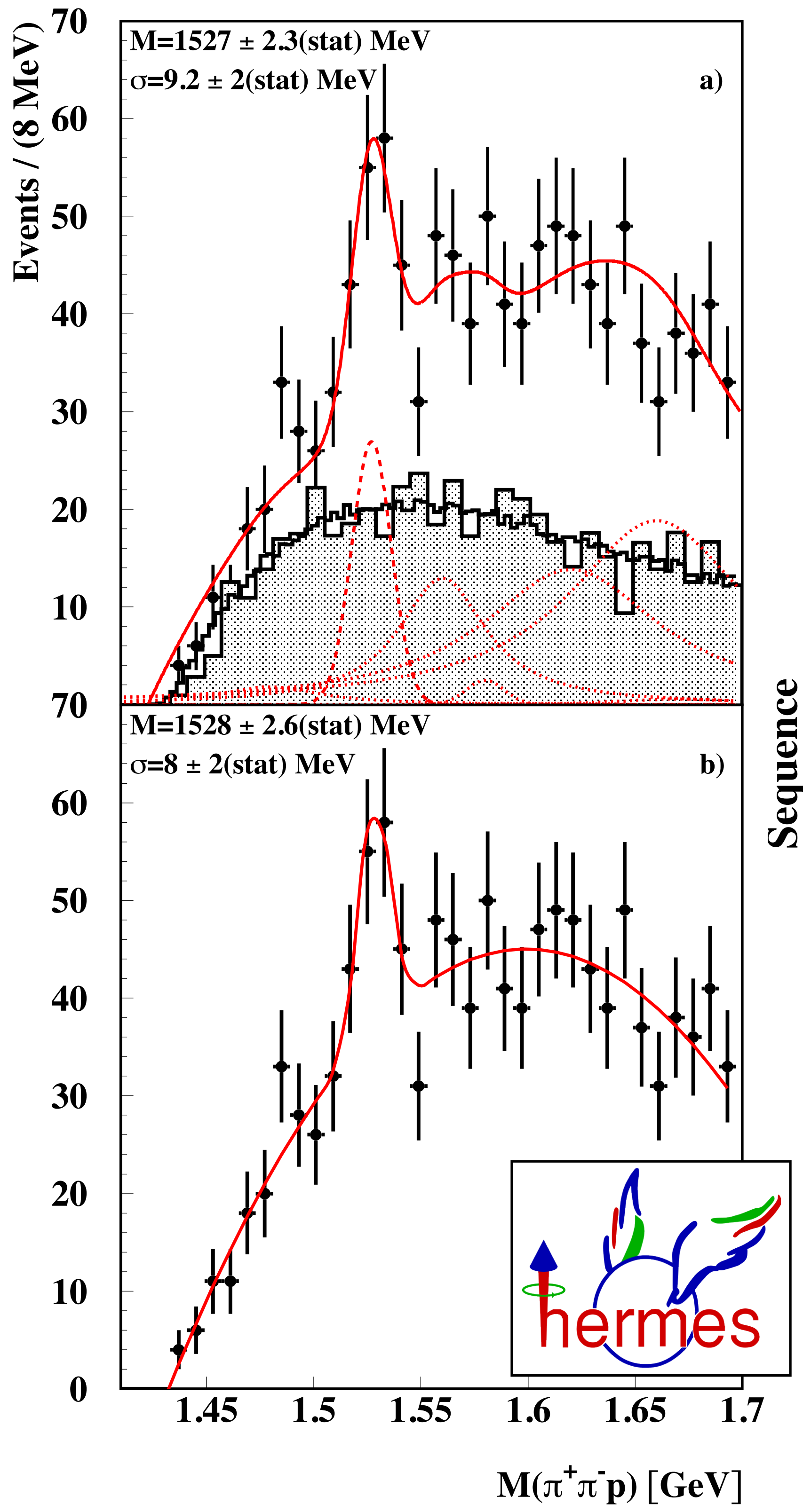
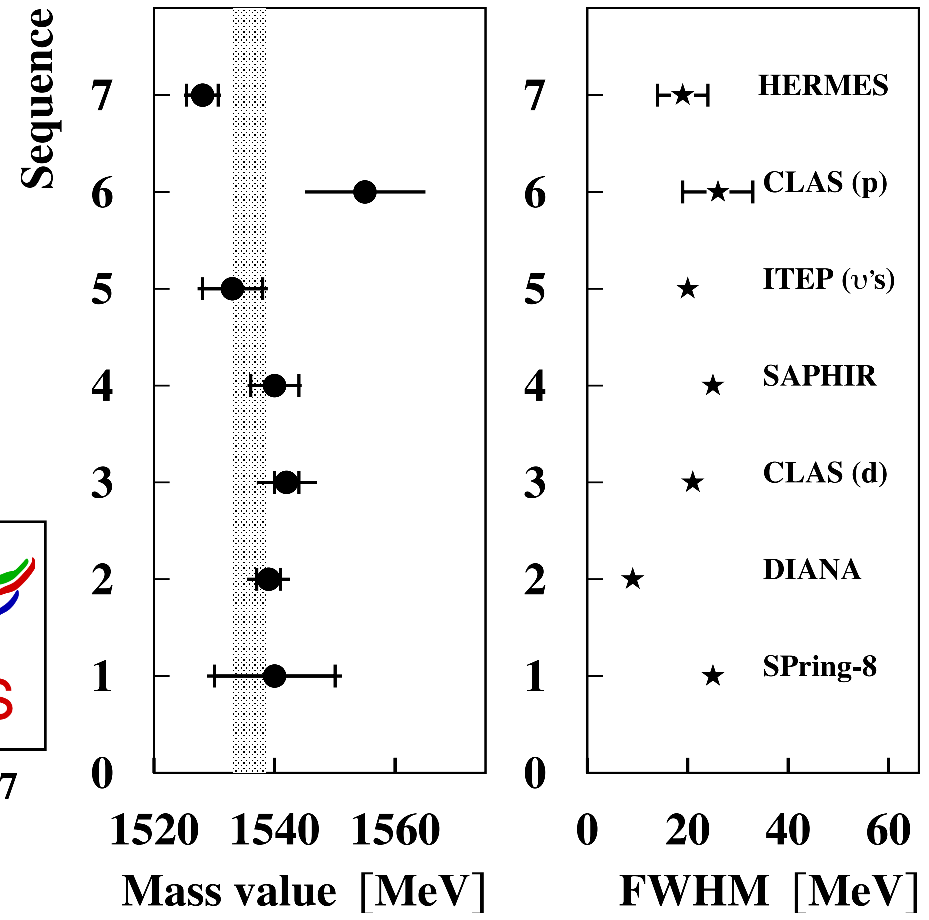
~4 σ evidence at HERMES

[Phys. Lett. B 585 (2004) 213]





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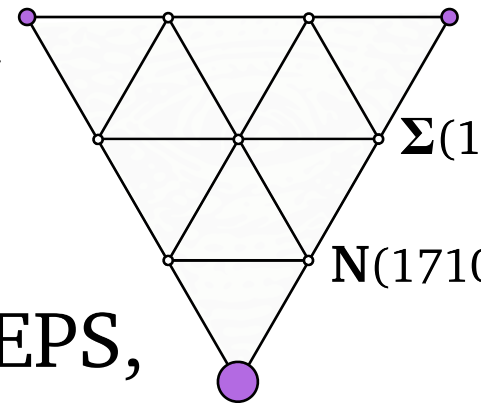

~4.5 σ evidence of Θ^+ at LEPS,

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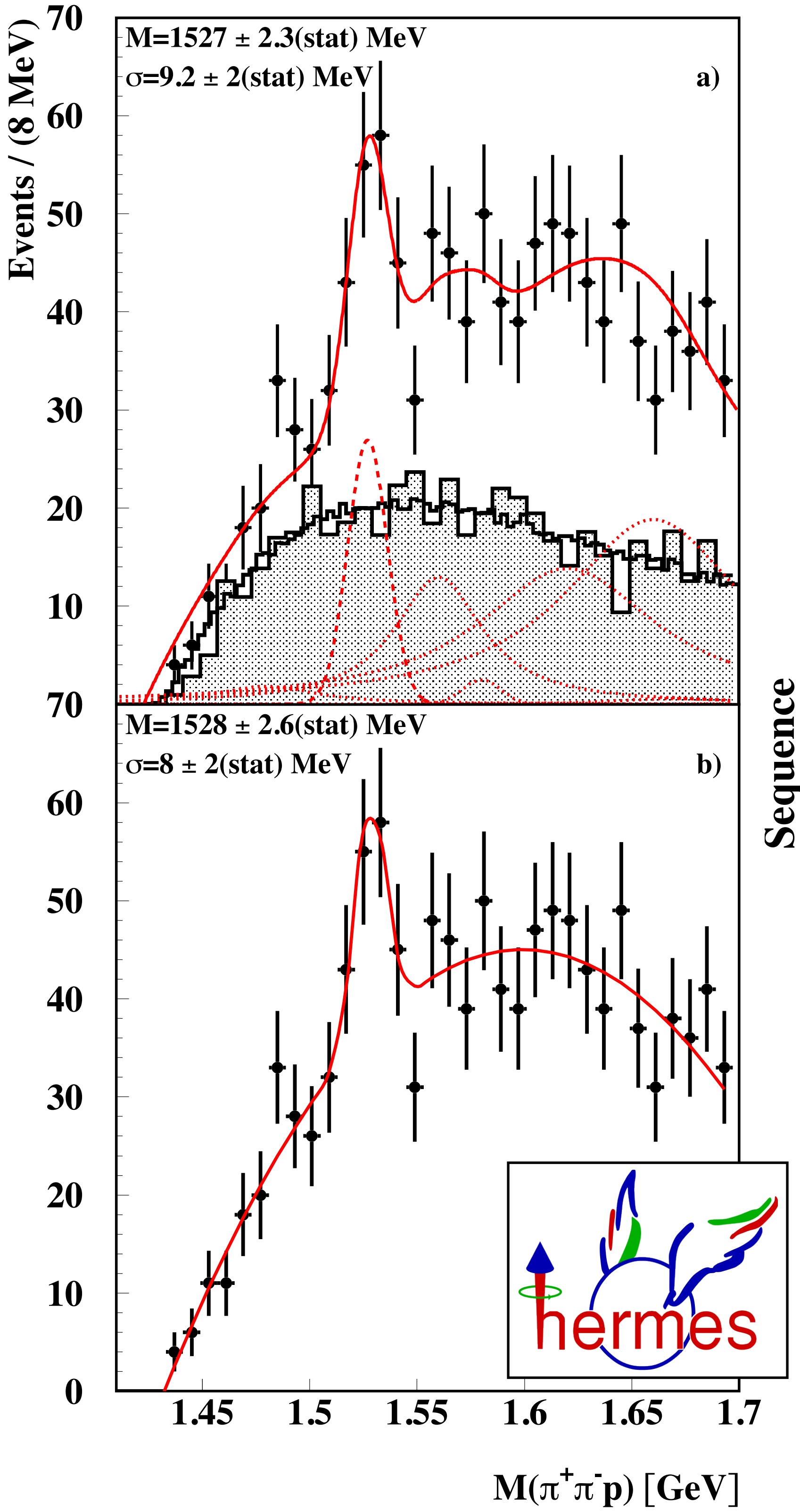
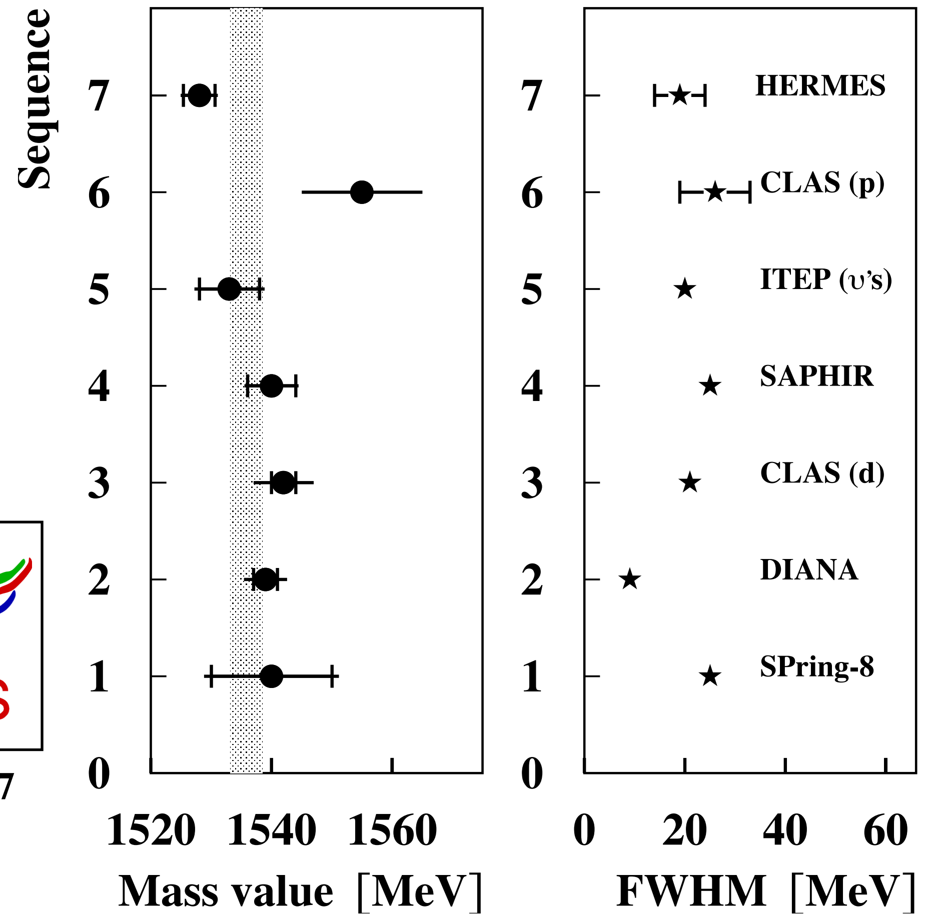


~4 σ evidence at **HERMES**

Phys. Lett. B 585 (2004) 213

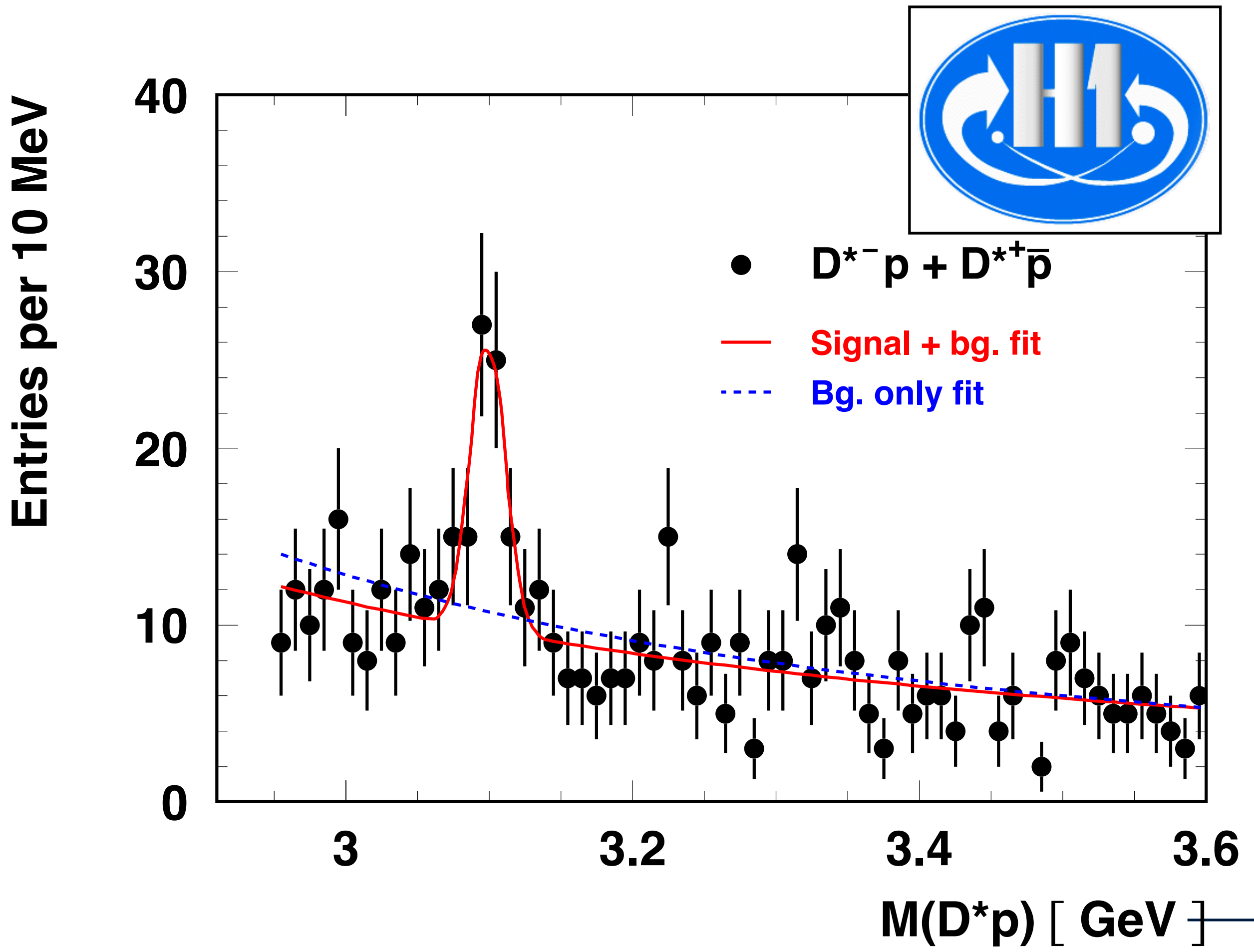


Θ^0_c

$uudd\bar{c}$

~5.5 σ evidence at **H1**

Phys. Lett. B 588 (2004) 17-28



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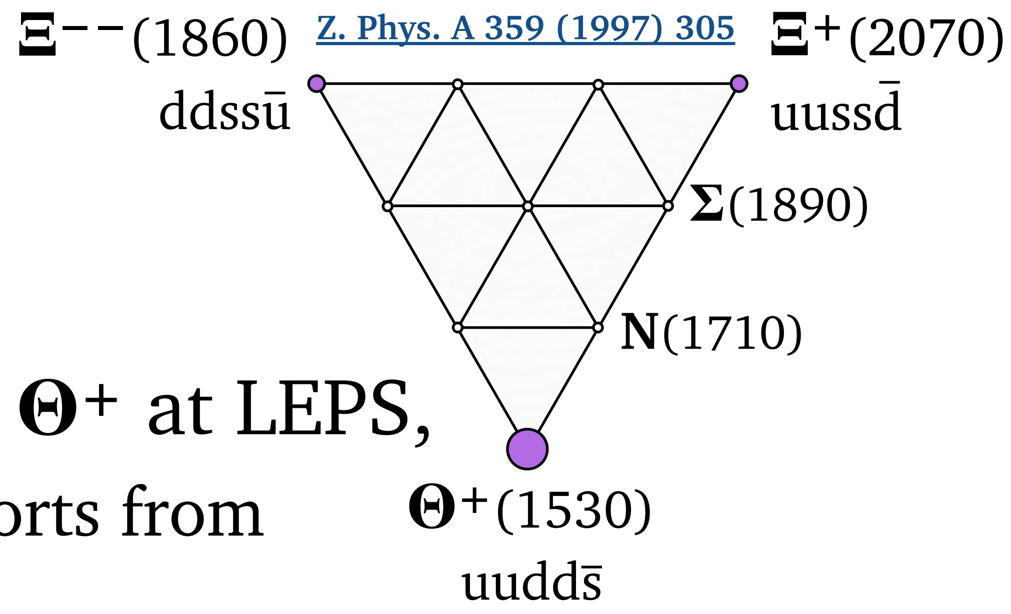
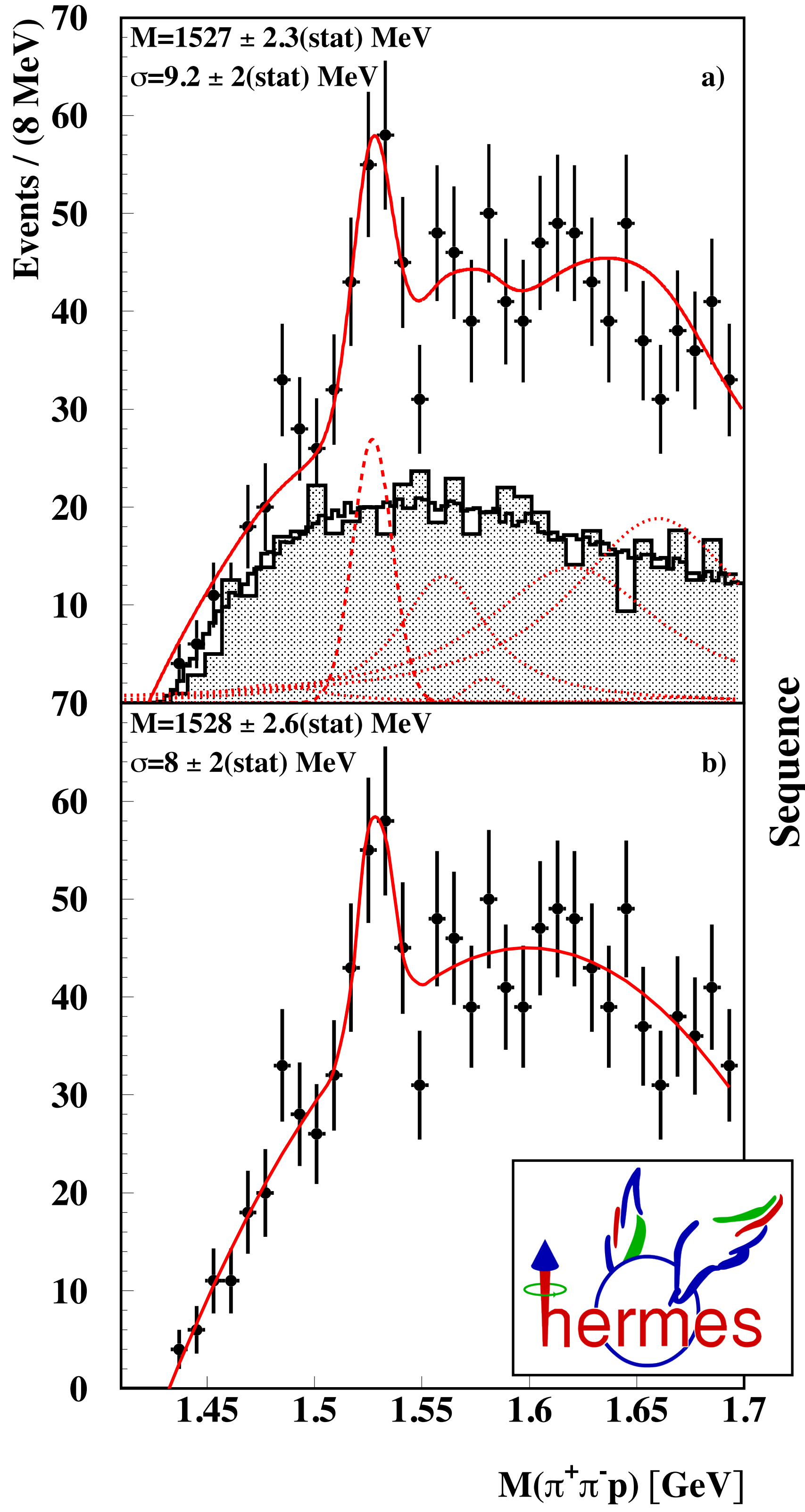
Z. Phys. A 359 (1997) 305



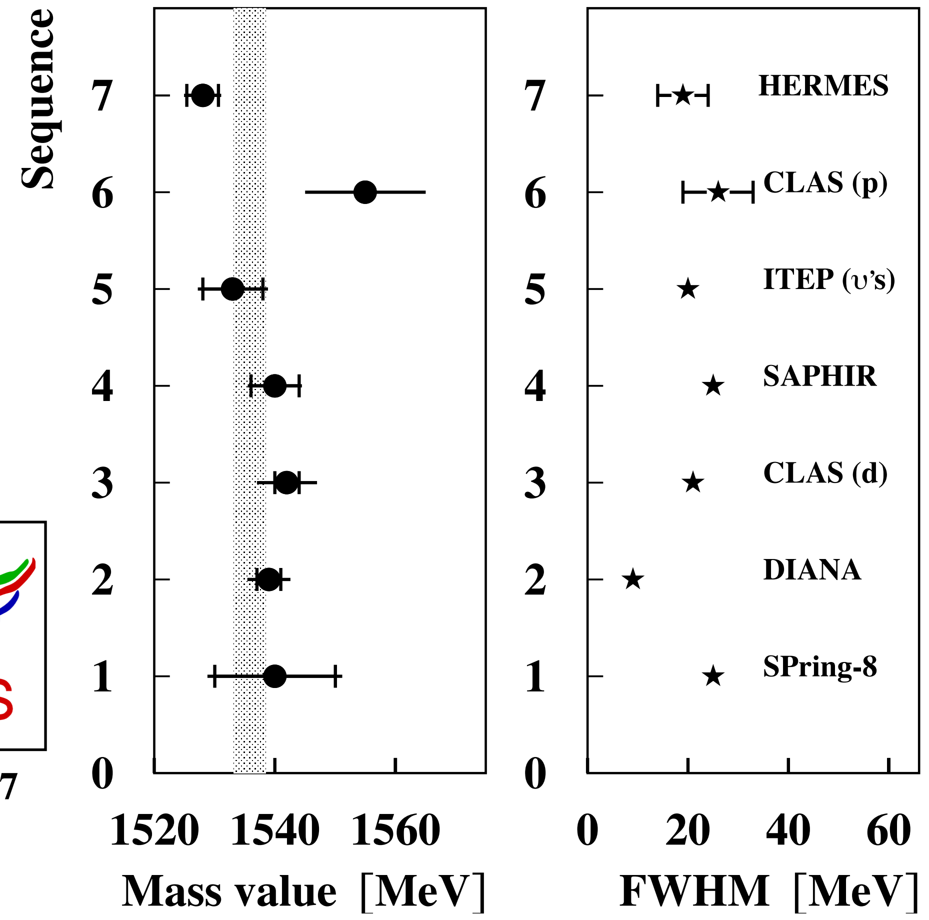
~4.5 σ evidence of Θ^{+} at LEPS,

followed by ~4 σ reports from 9 more experiments



~4 σ evidence at **HERMES**

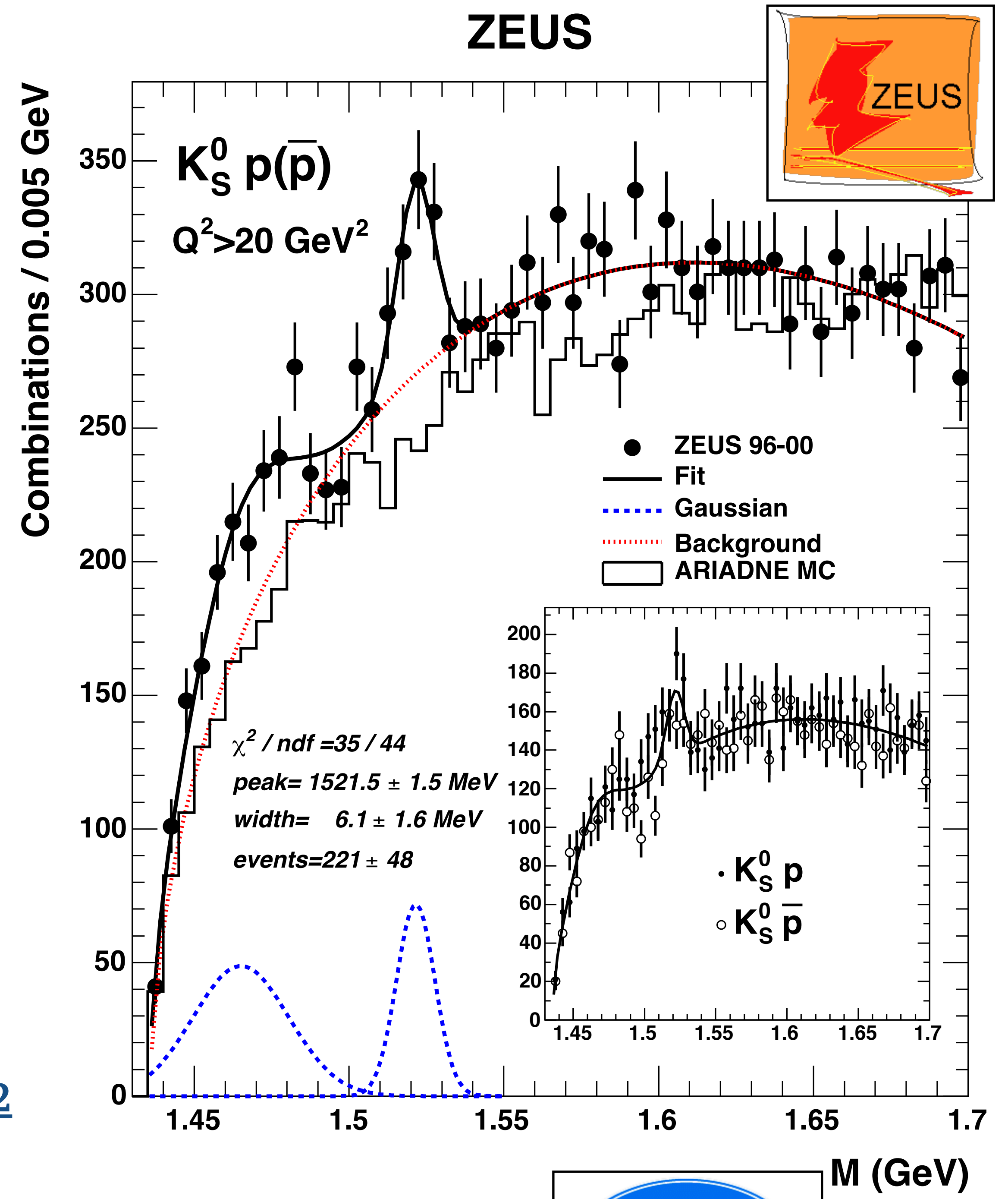
Phys. Lett. B 585 (2004) 213

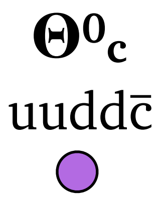


~4 σ evidence at **ZEUS**

+ evidence for $\bar{u}\bar{u}\bar{d}\bar{d}s$

Phys. Lett. B 591 (2004) 7-22





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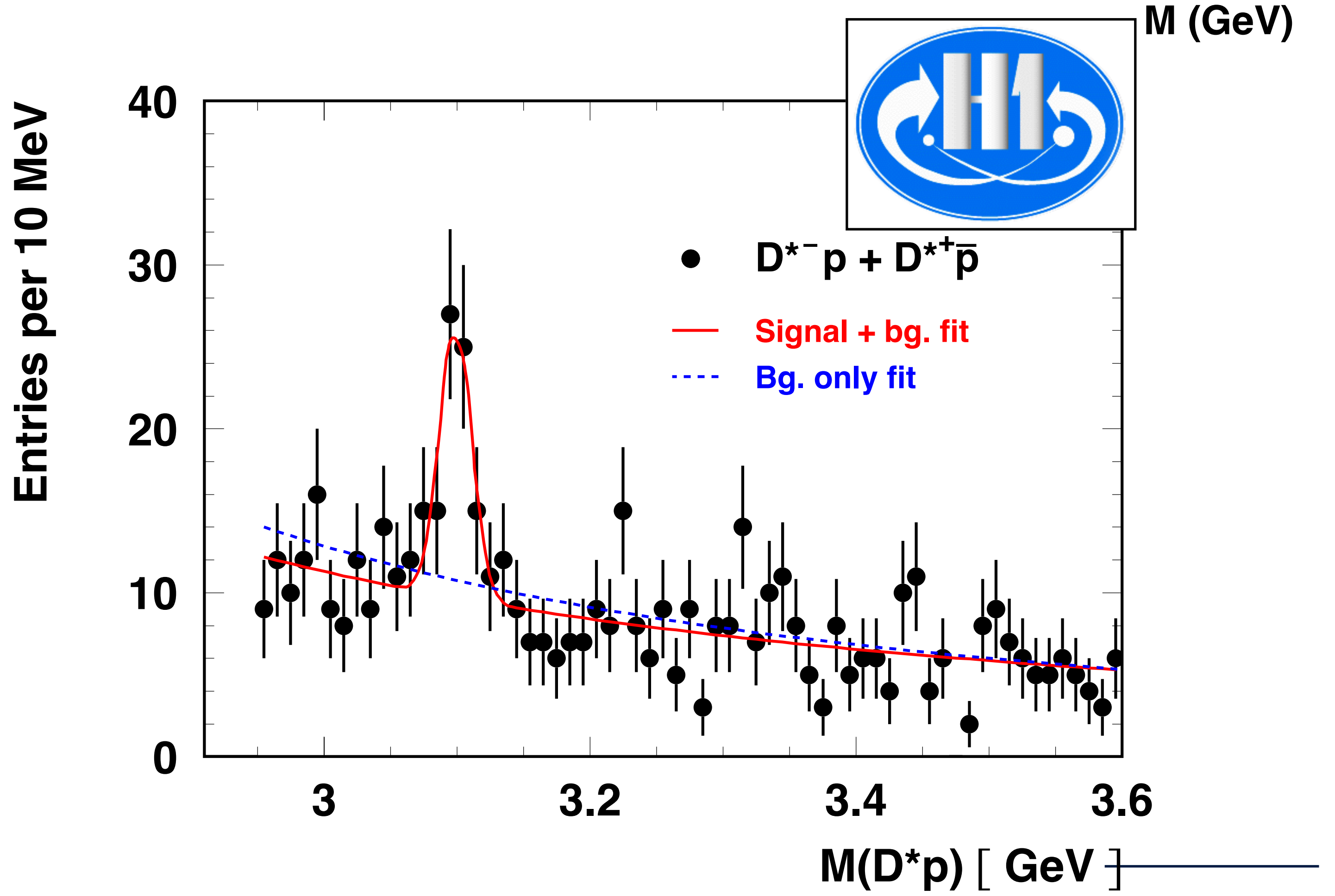

2003 - 2004:

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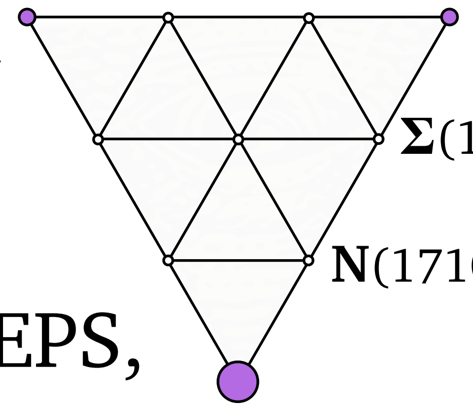


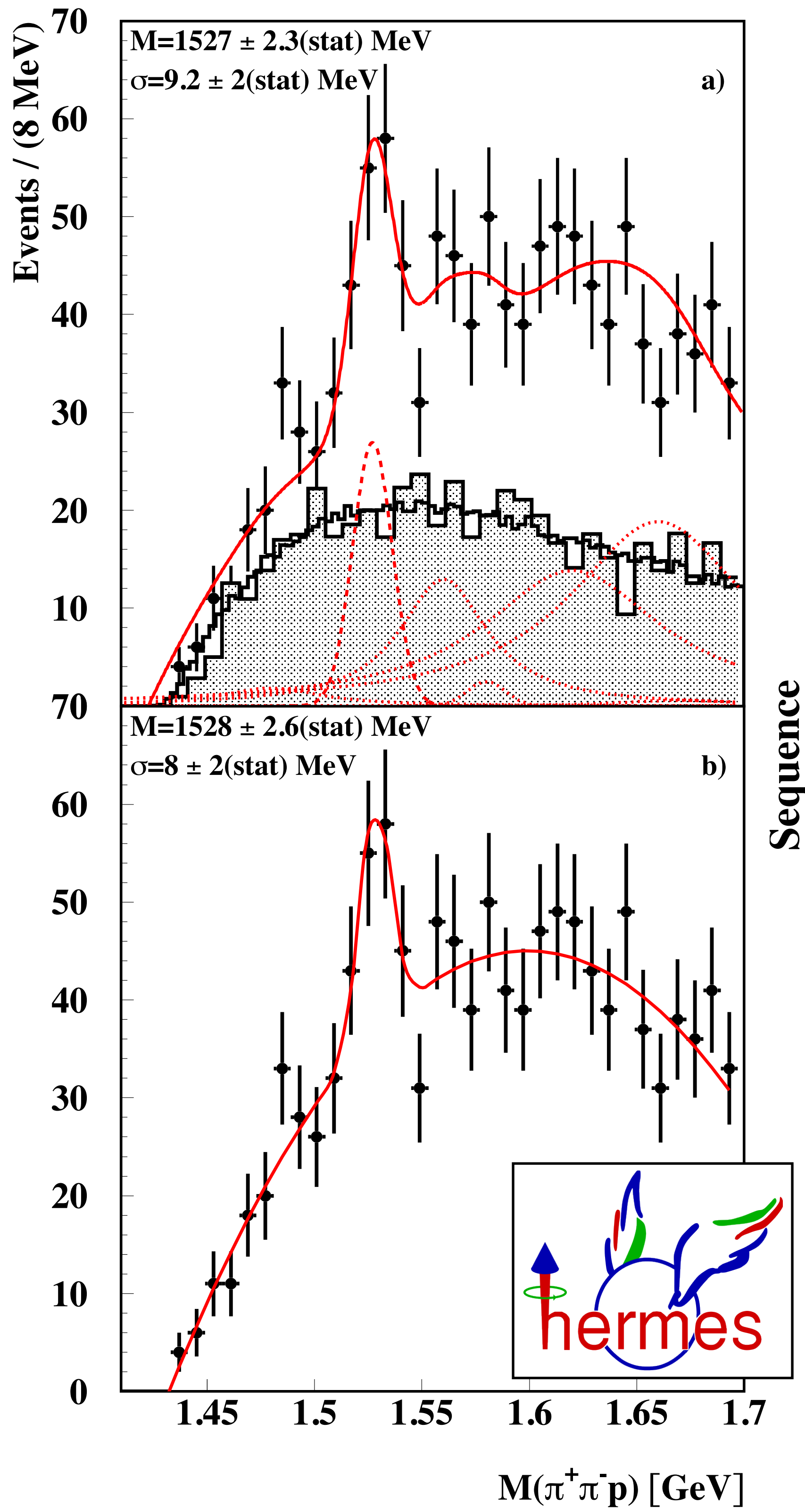
~4.5 σ evidence of Θ^+ at LEPS,
followed by ~4 σ reports from
9 more experiments

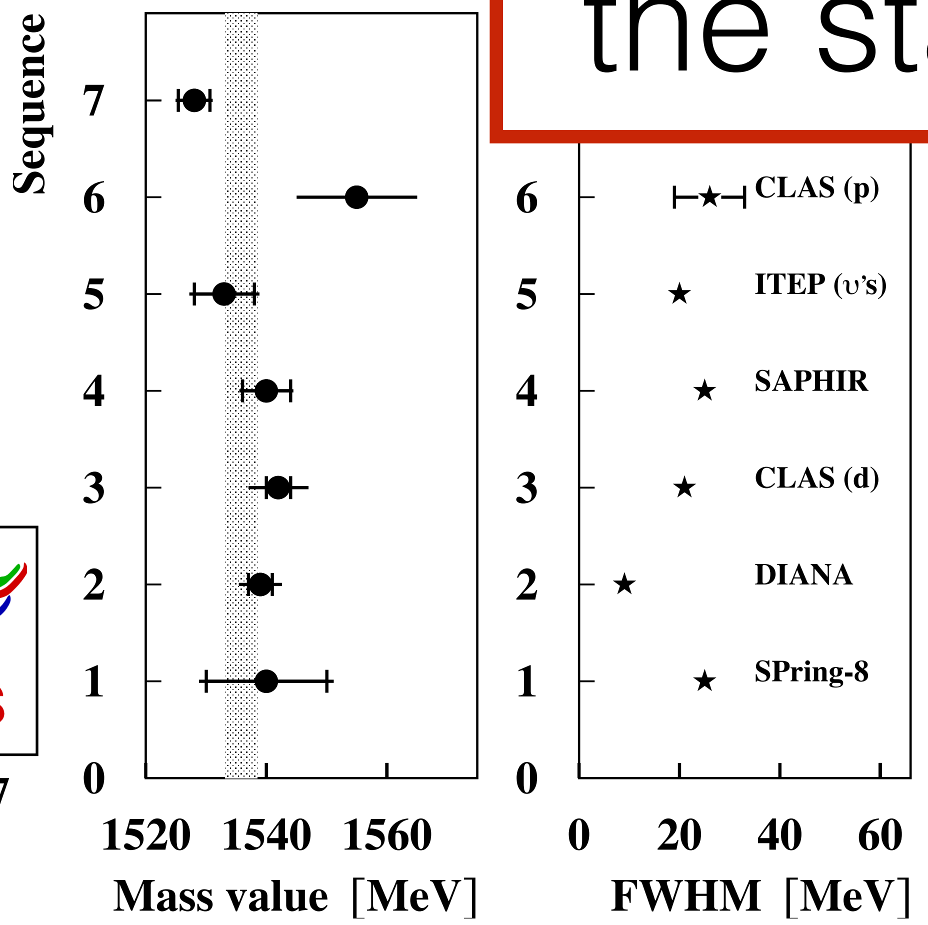
~4 σ evide

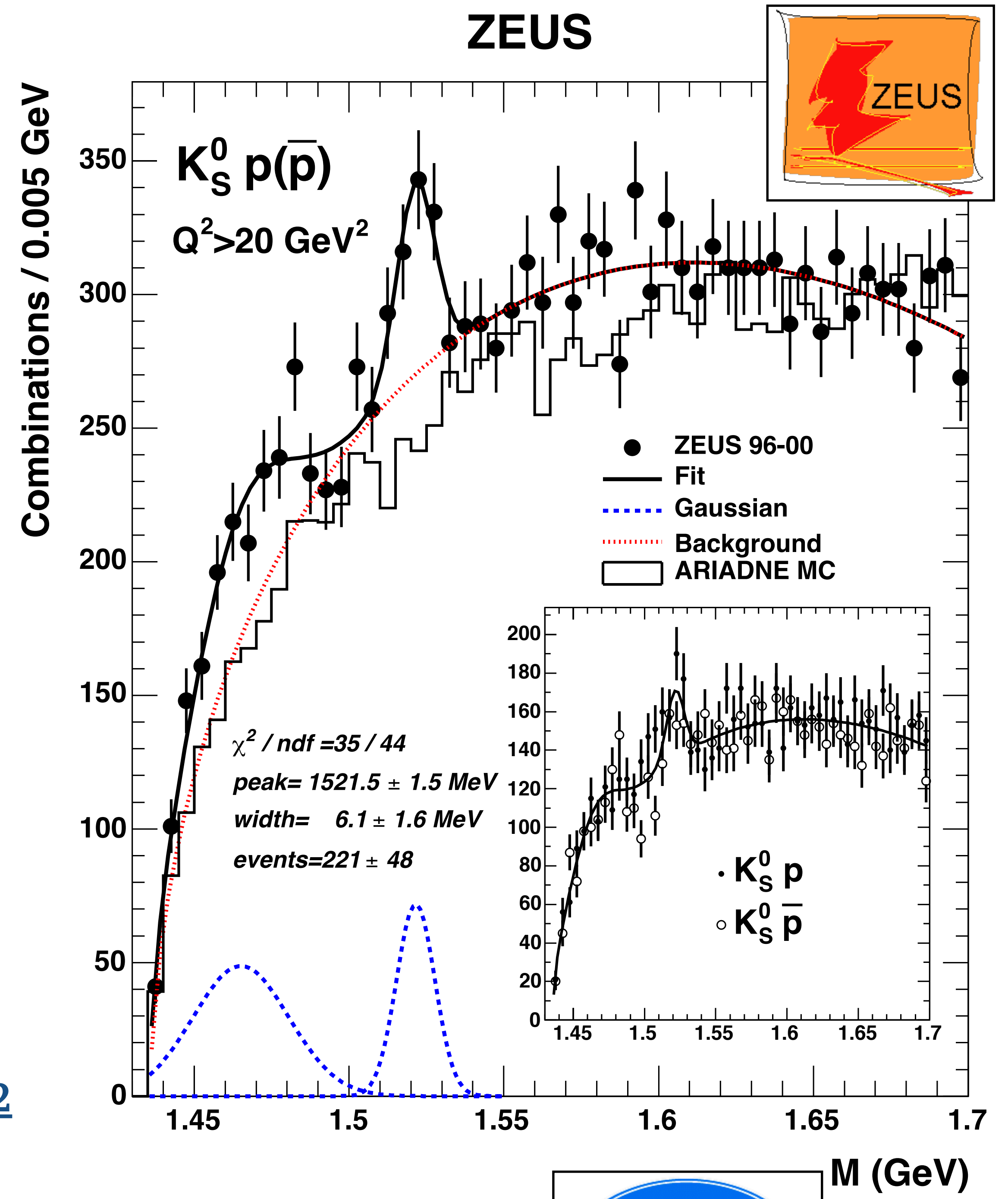
Phys

04) 7-22

PDG14 set Θ^+
the status of ★★★☆







Θ^0_c
uuddc̄

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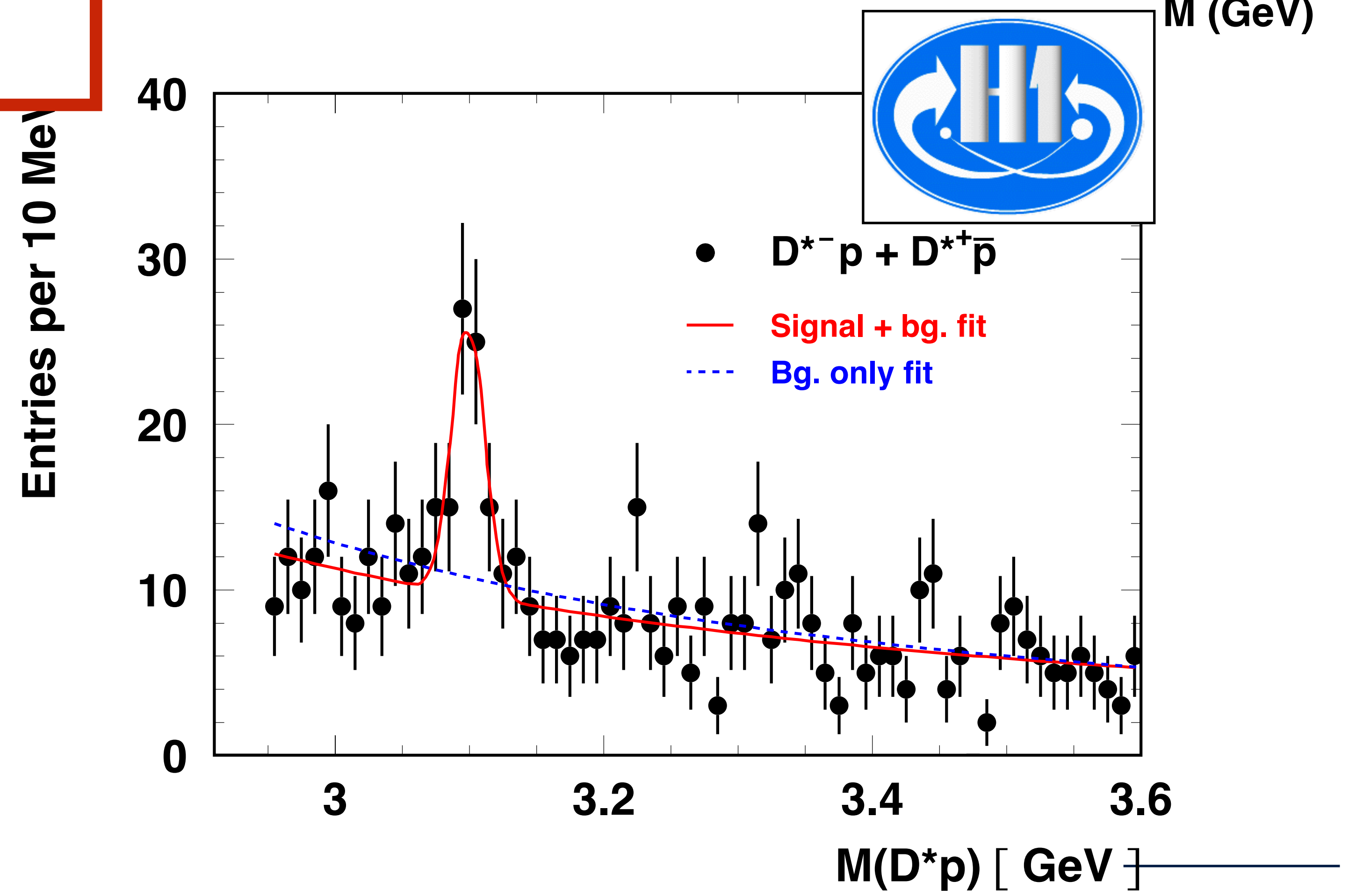
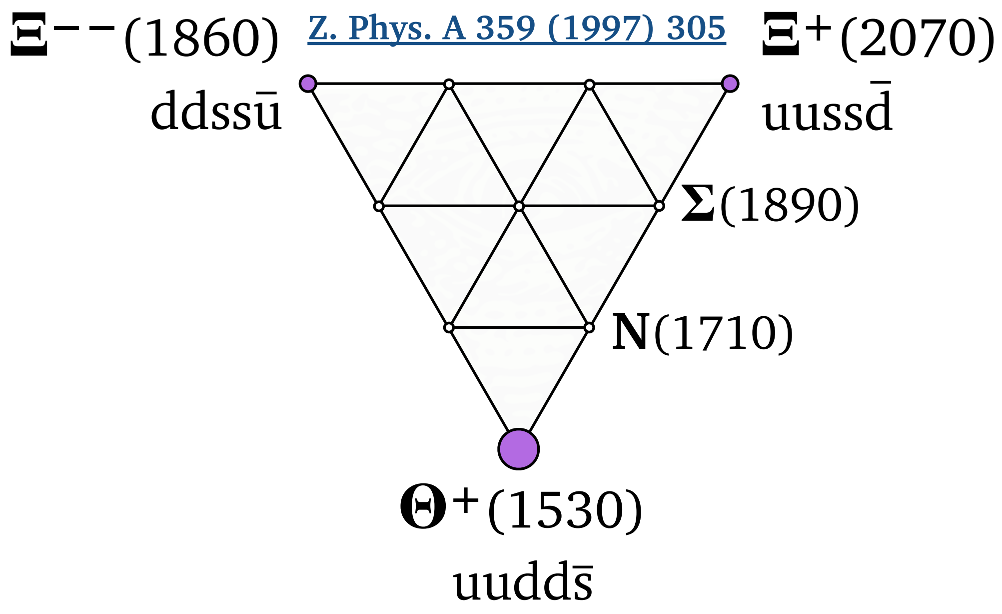
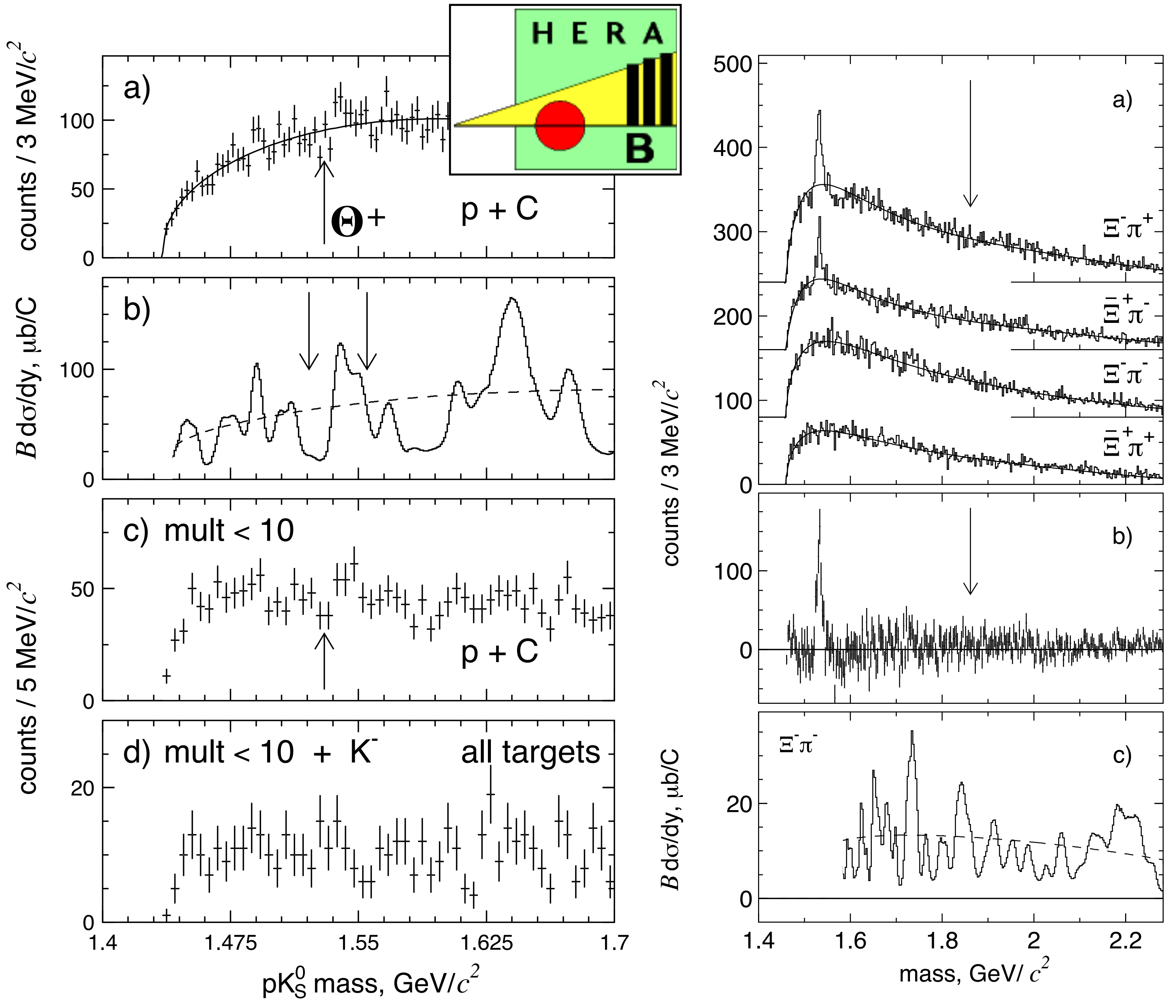
Phys. Lett. B 588 (2004) 17-28



2004 - 2005:

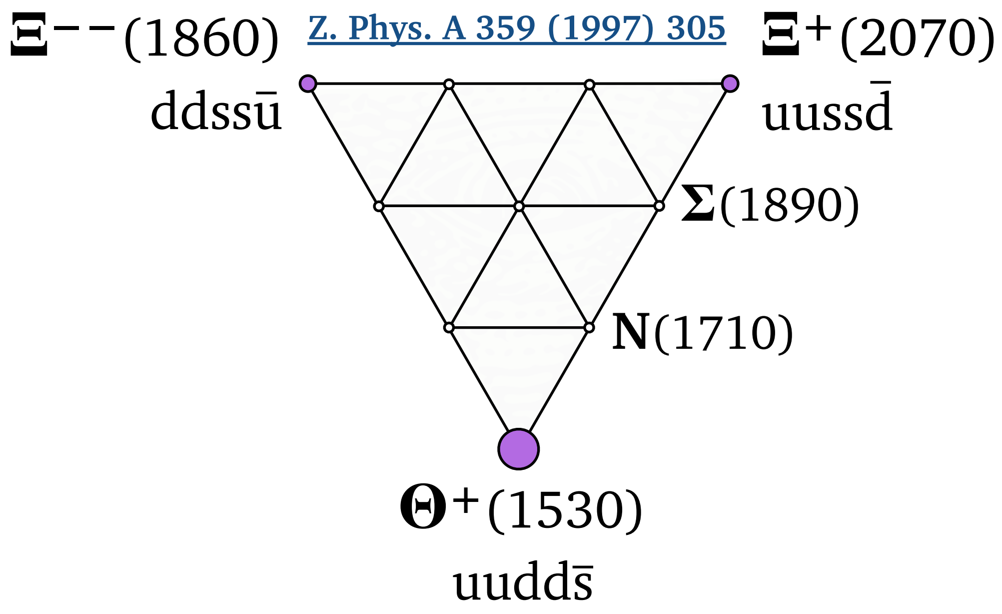


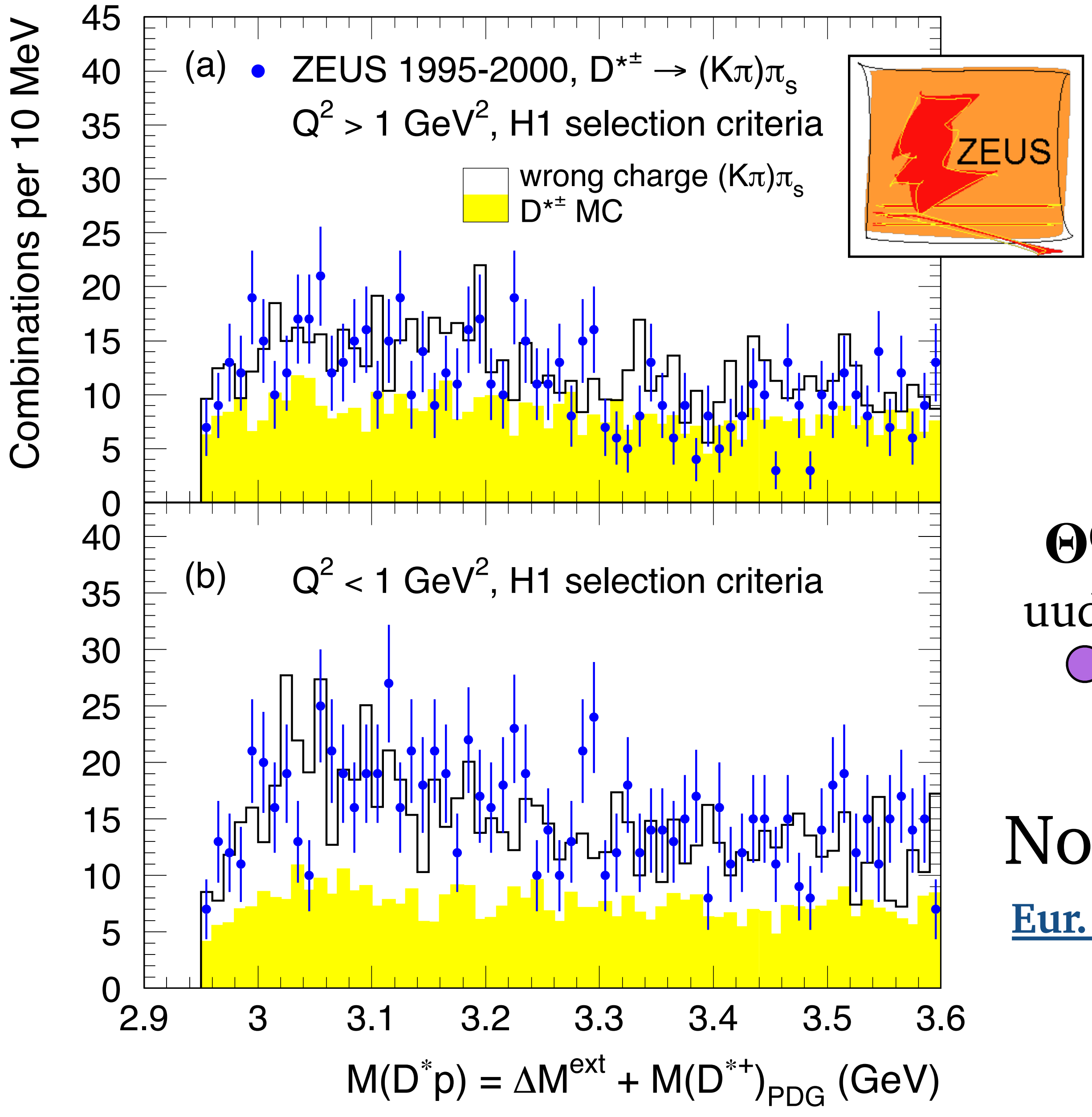


No **Θ⁺** or **Ξ⁻⁻** observed by **HERA-B**

Phys. Rev. Lett. 93, 212003 (2004)

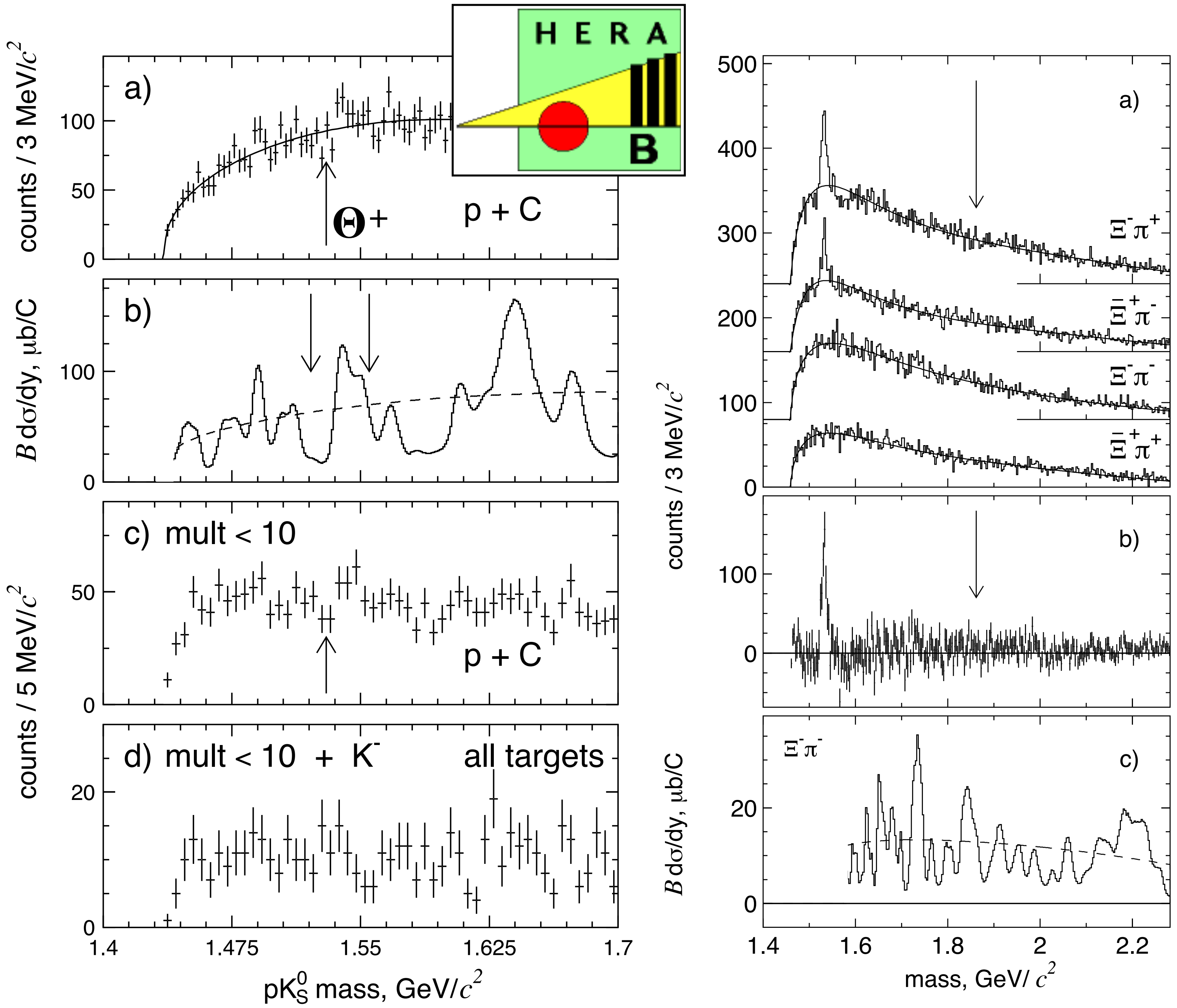
2004 - 2005:





Θ^0_c

$uudd\bar{c}$



No Θ^+ or Ξ^{--} observed by **HERA-B**

Phys. Rev. Lett. 93, 212003 (2004)

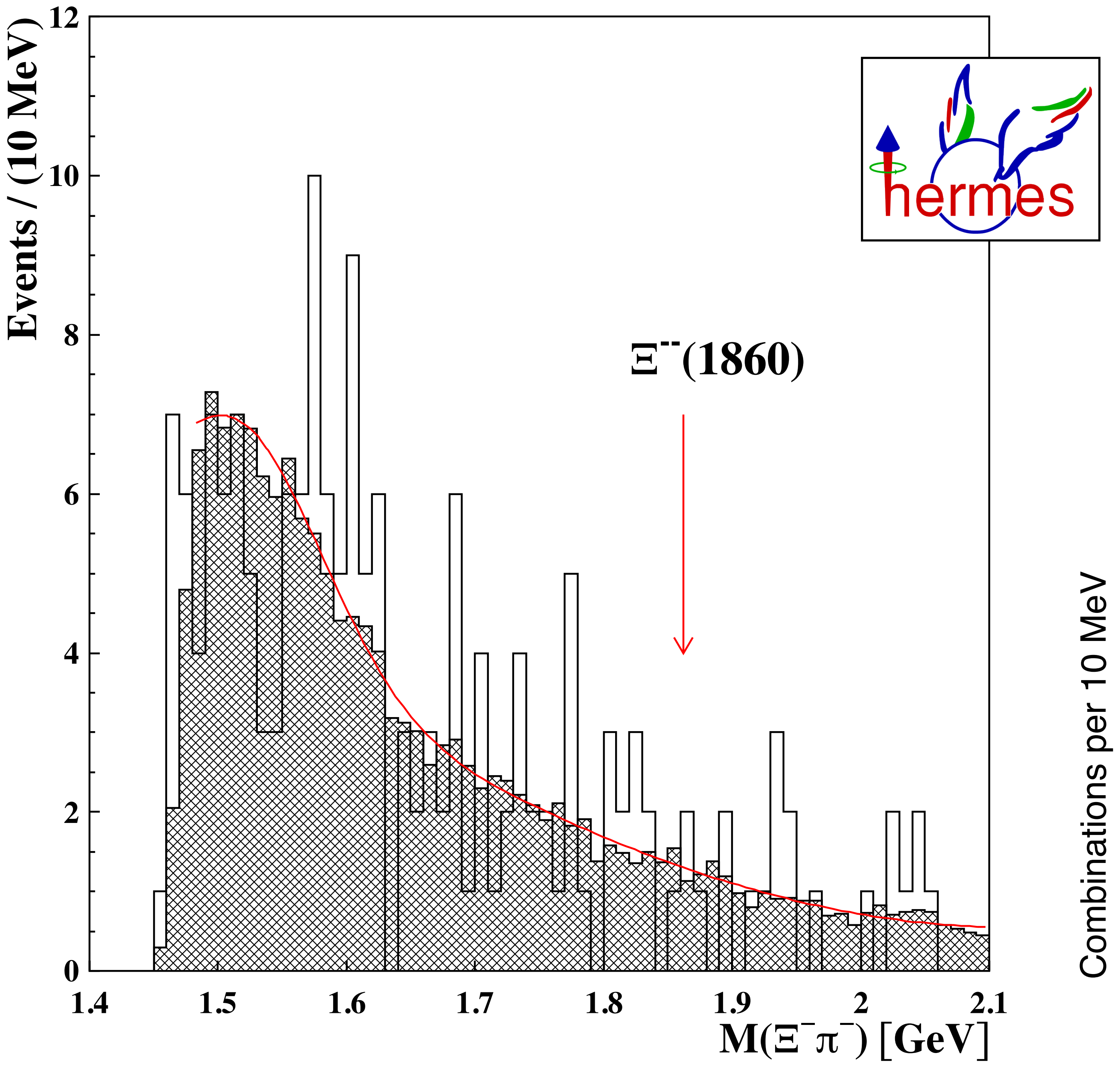
No Θ^0_c peak observed in **ZEUS** data

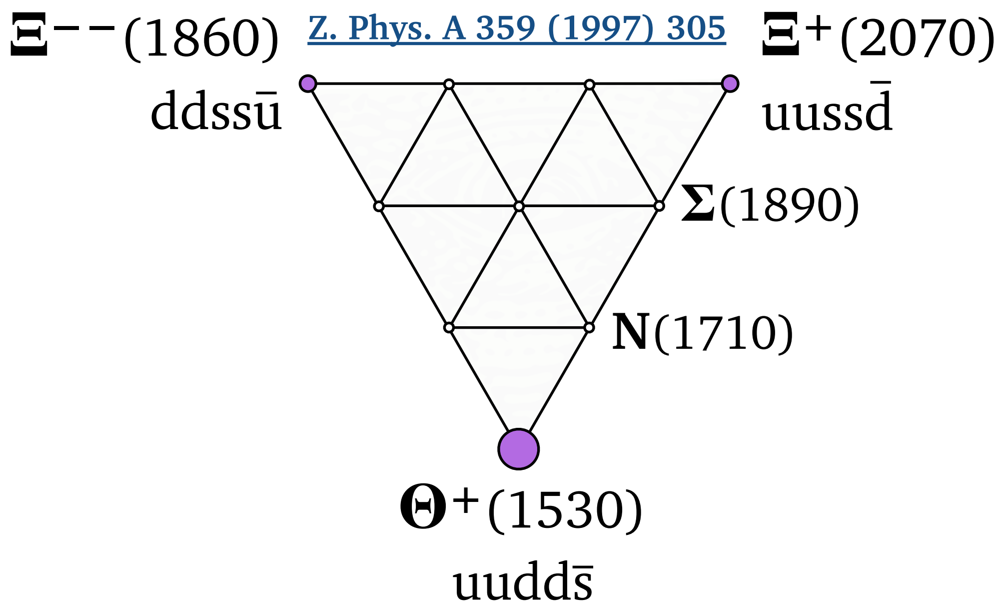
Eur. Phys. J. C 38 (2004) 29-41

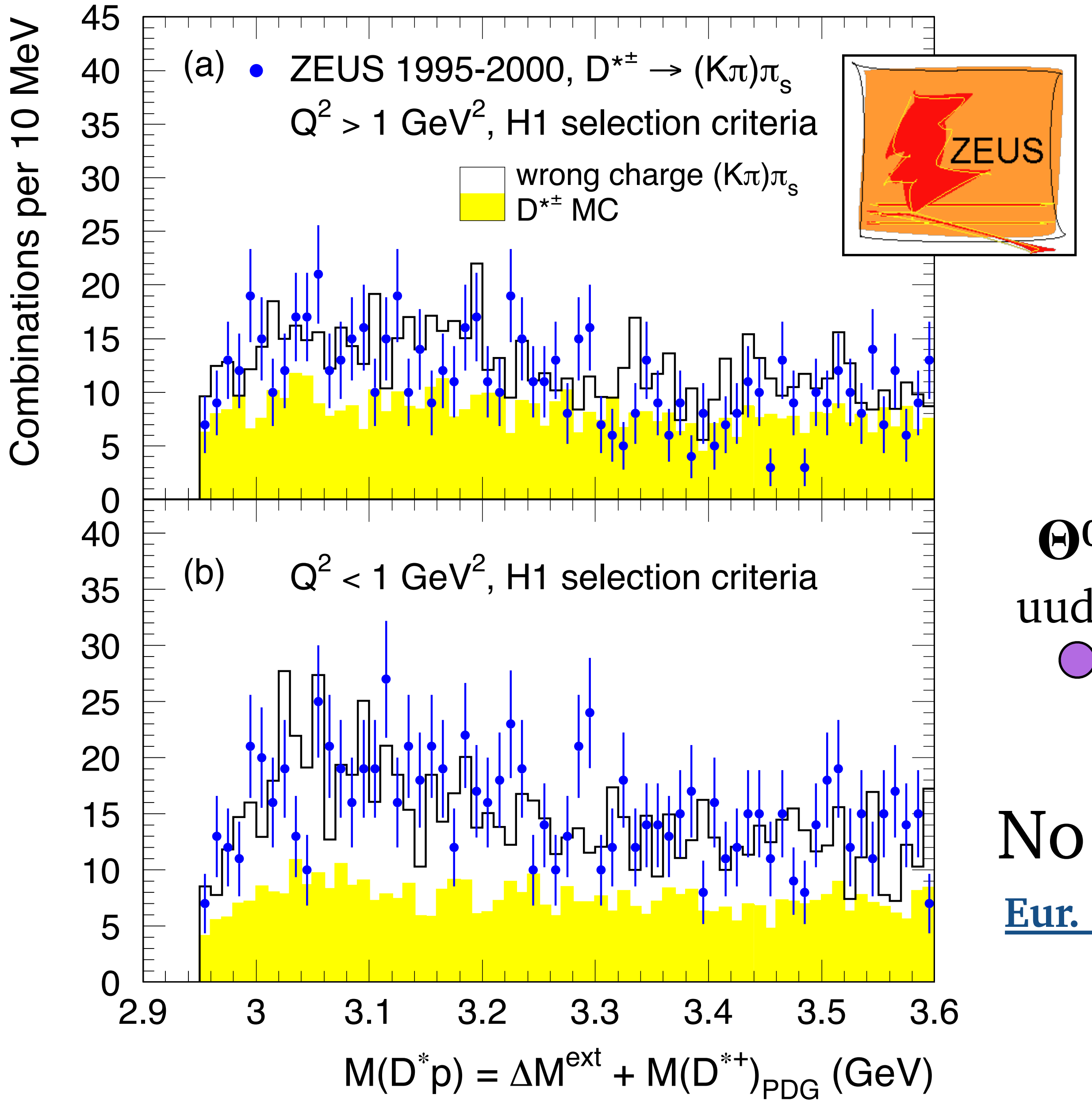
2004 - 2005:

No Ξ^{--} peak observed by **HERMES**

Phys. Rev. D 71 (2005) 032004

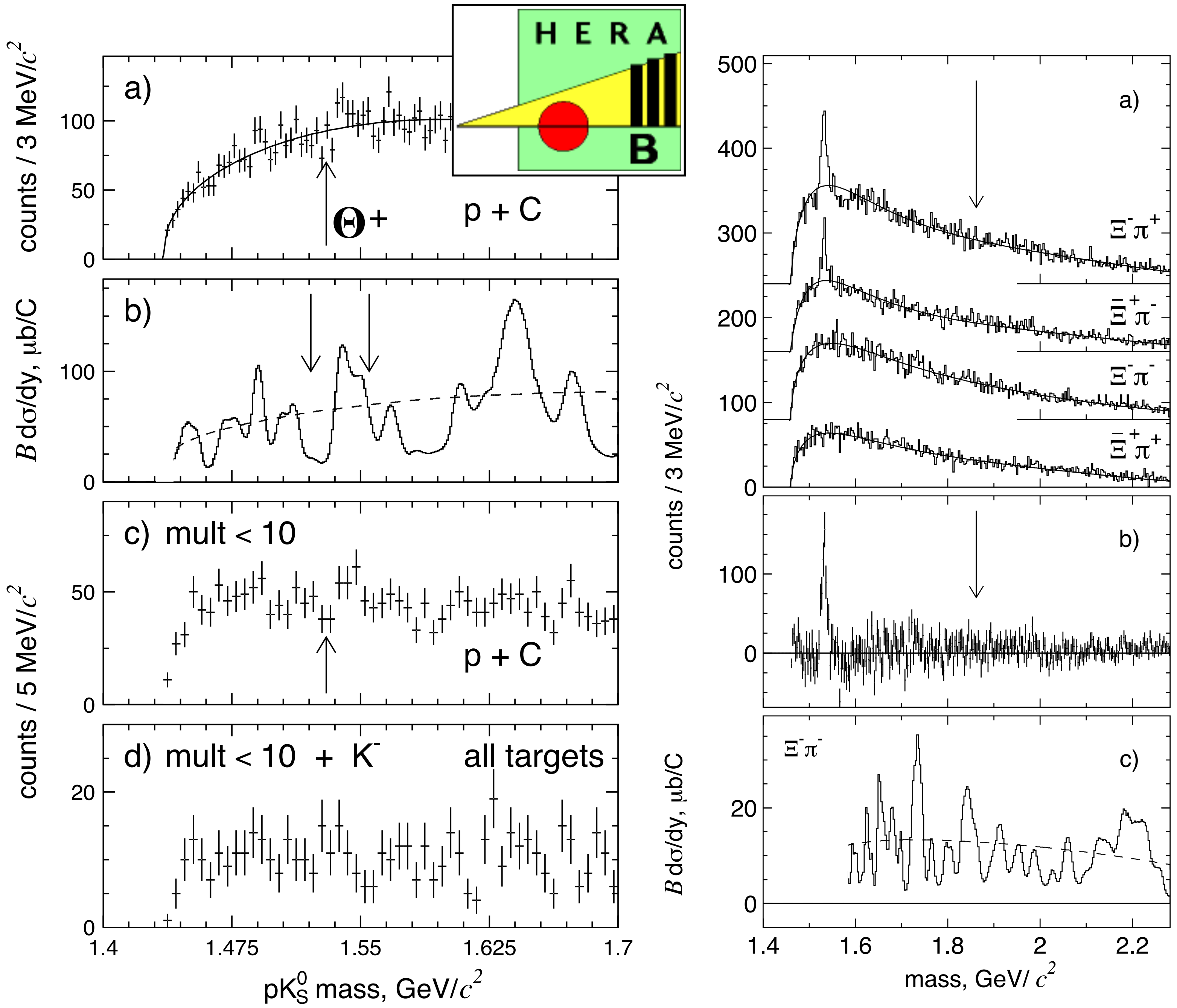






Θ^0_c

$uudd\bar{c}$



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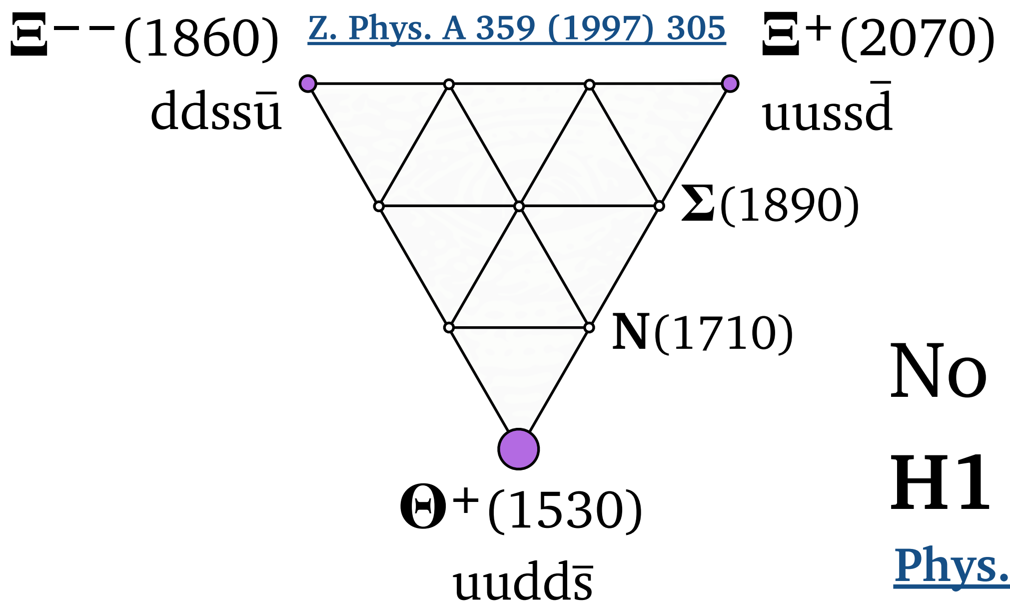
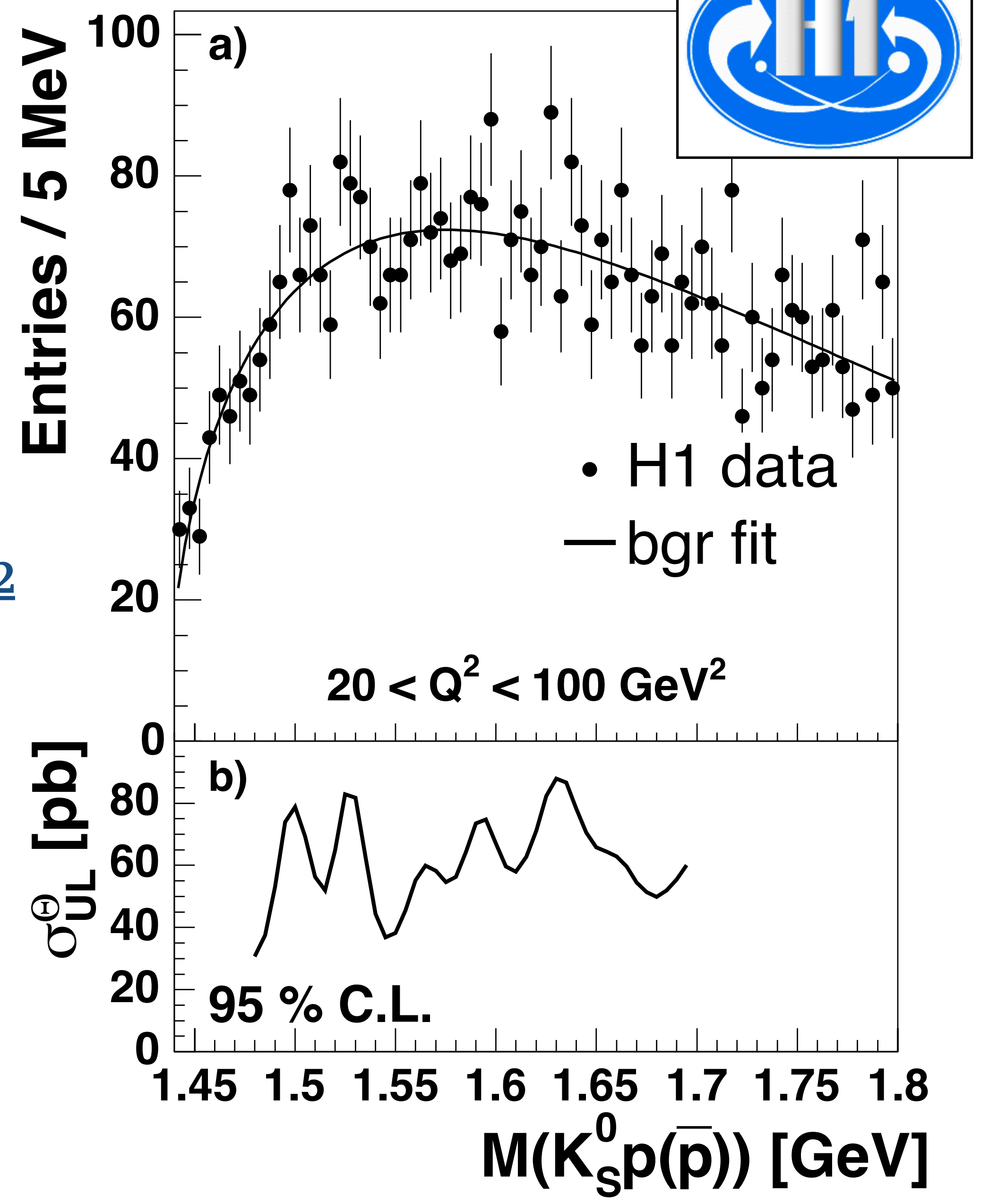
2006 - 2016:

No Θ^+ peak observed by Belle, later CLAS analysis and several other experiments



No Θ^+ peak in **H1** data

Phys. Lett. B 639 (2006) 202



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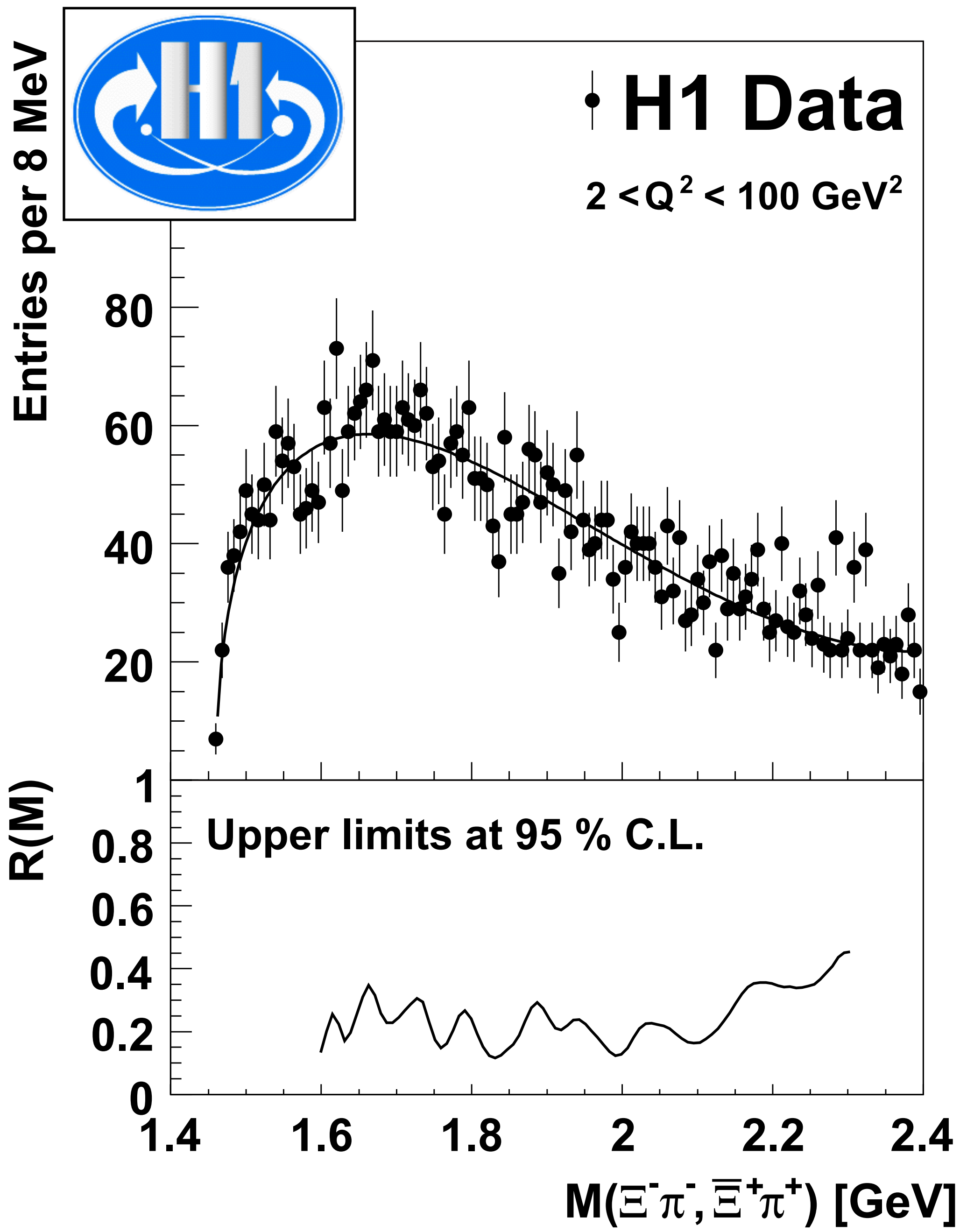
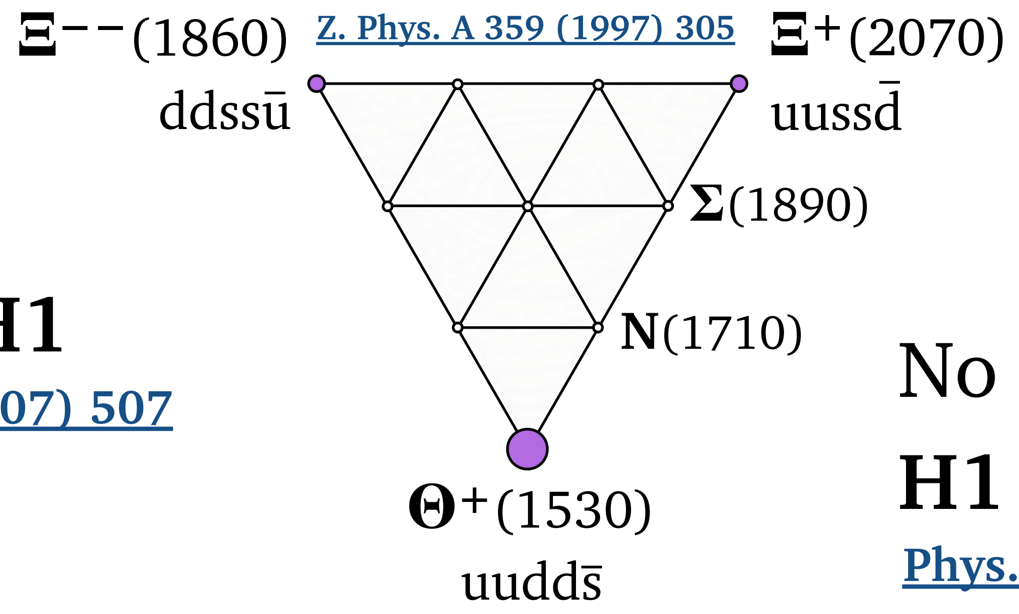


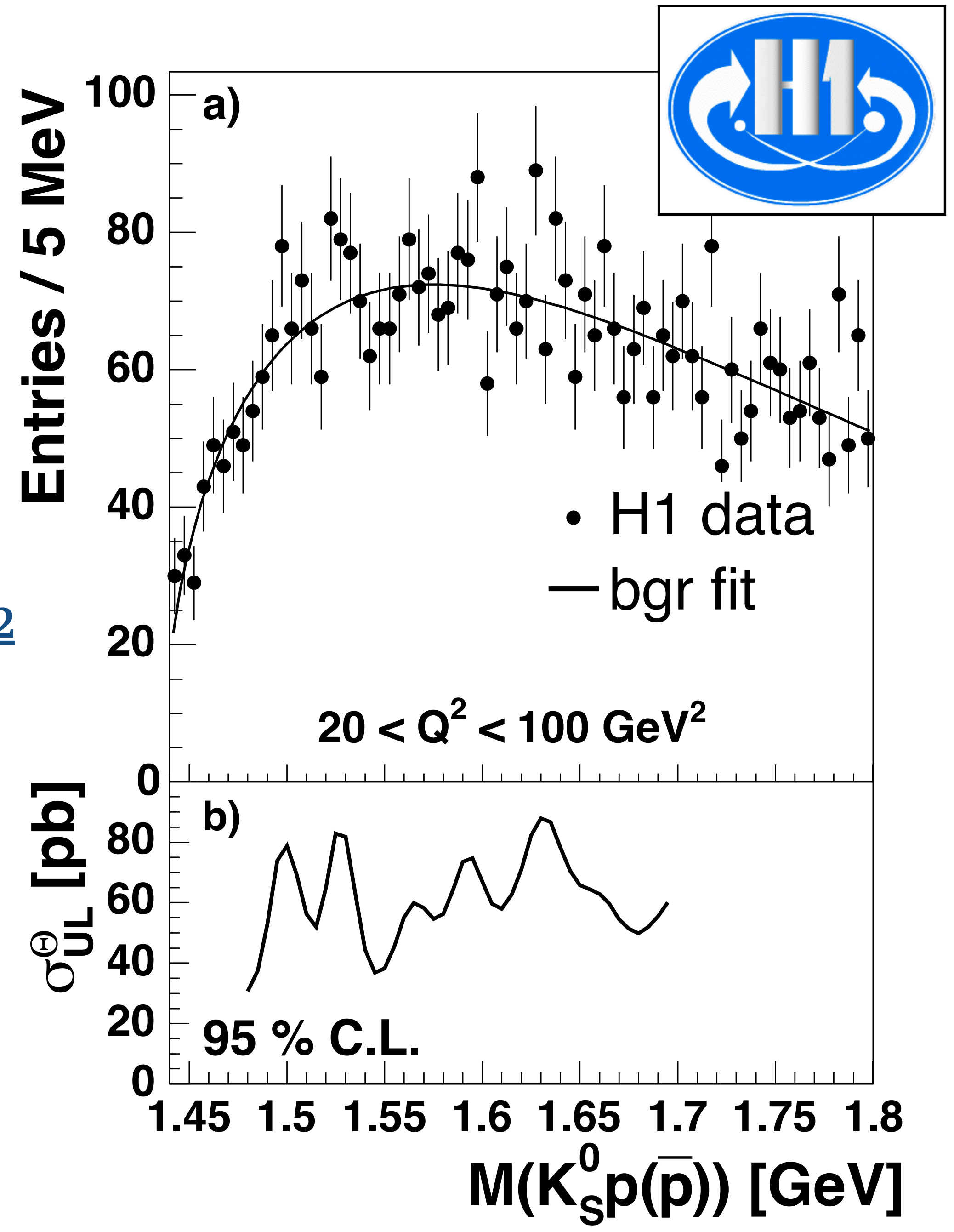
No Ξ^{--} peak observed by **H1**

Eur. Phys. J. C 52 (2007) 507



No Θ^+ peak in **H1** data

Phys. Lett. B 639 (2006) 202



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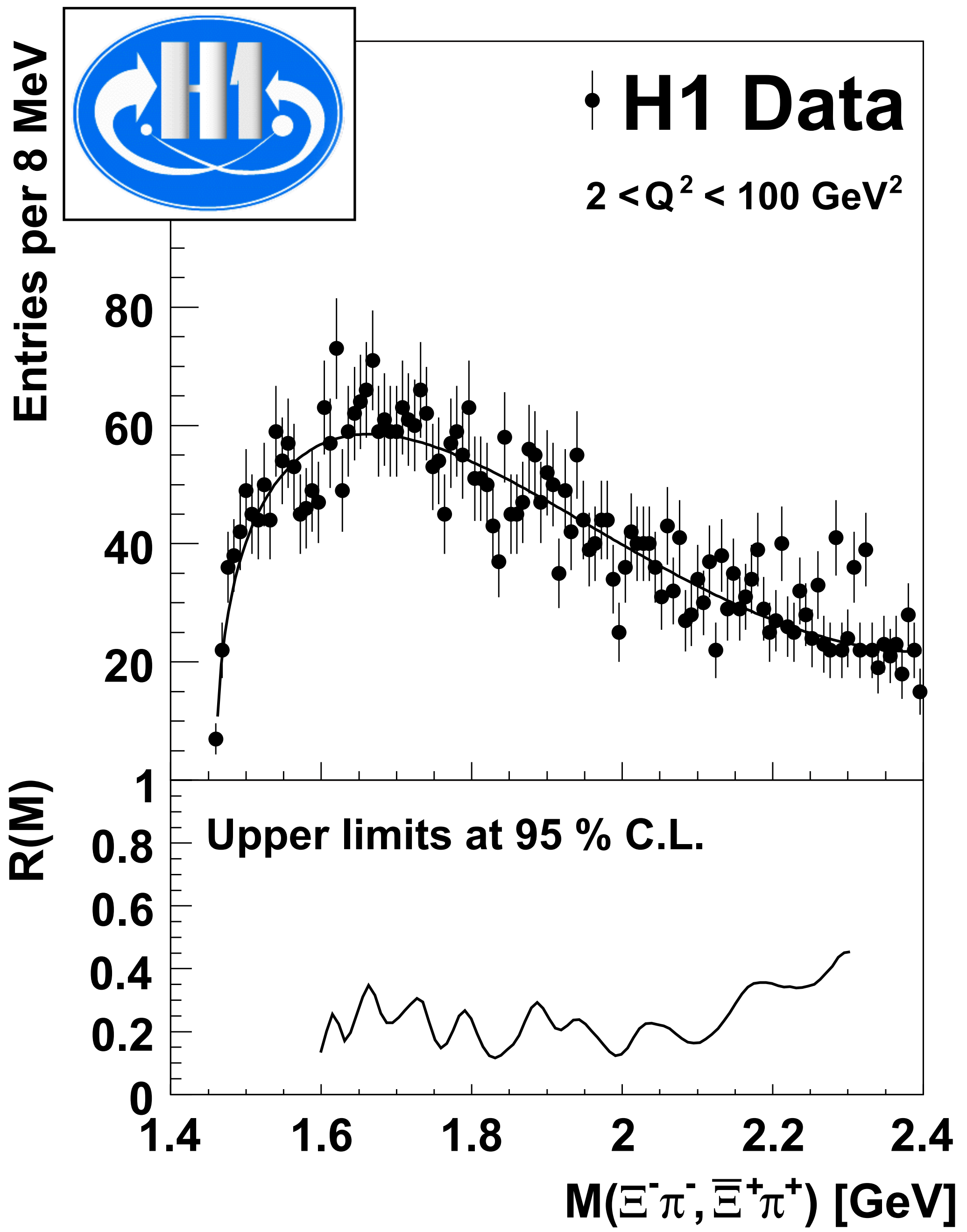
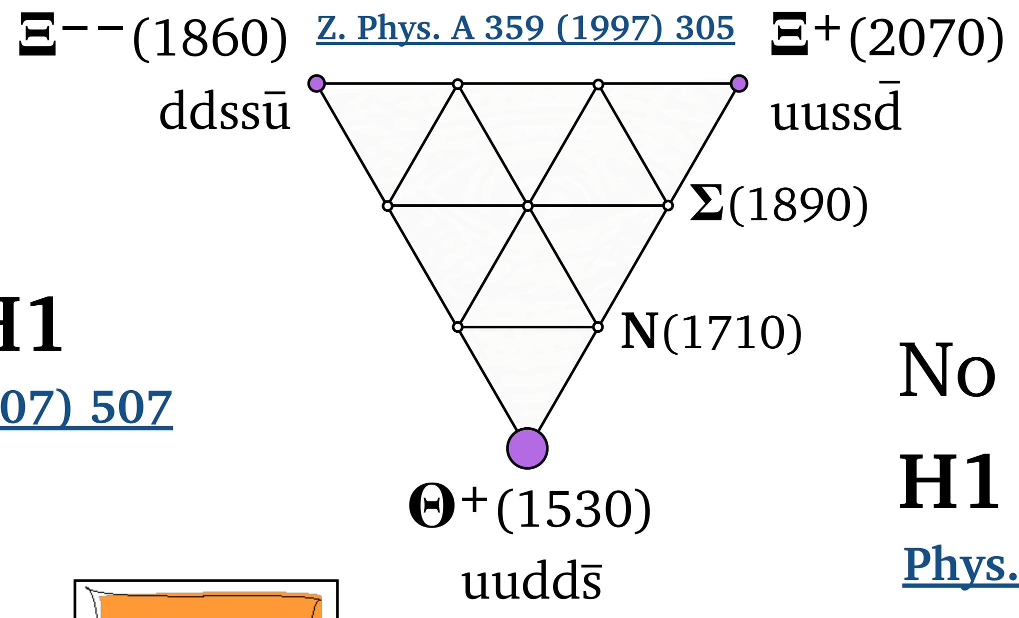


No Ξ^{--} peak observed by **H1**

Eur. Phys. J. C 52 (2007) 507



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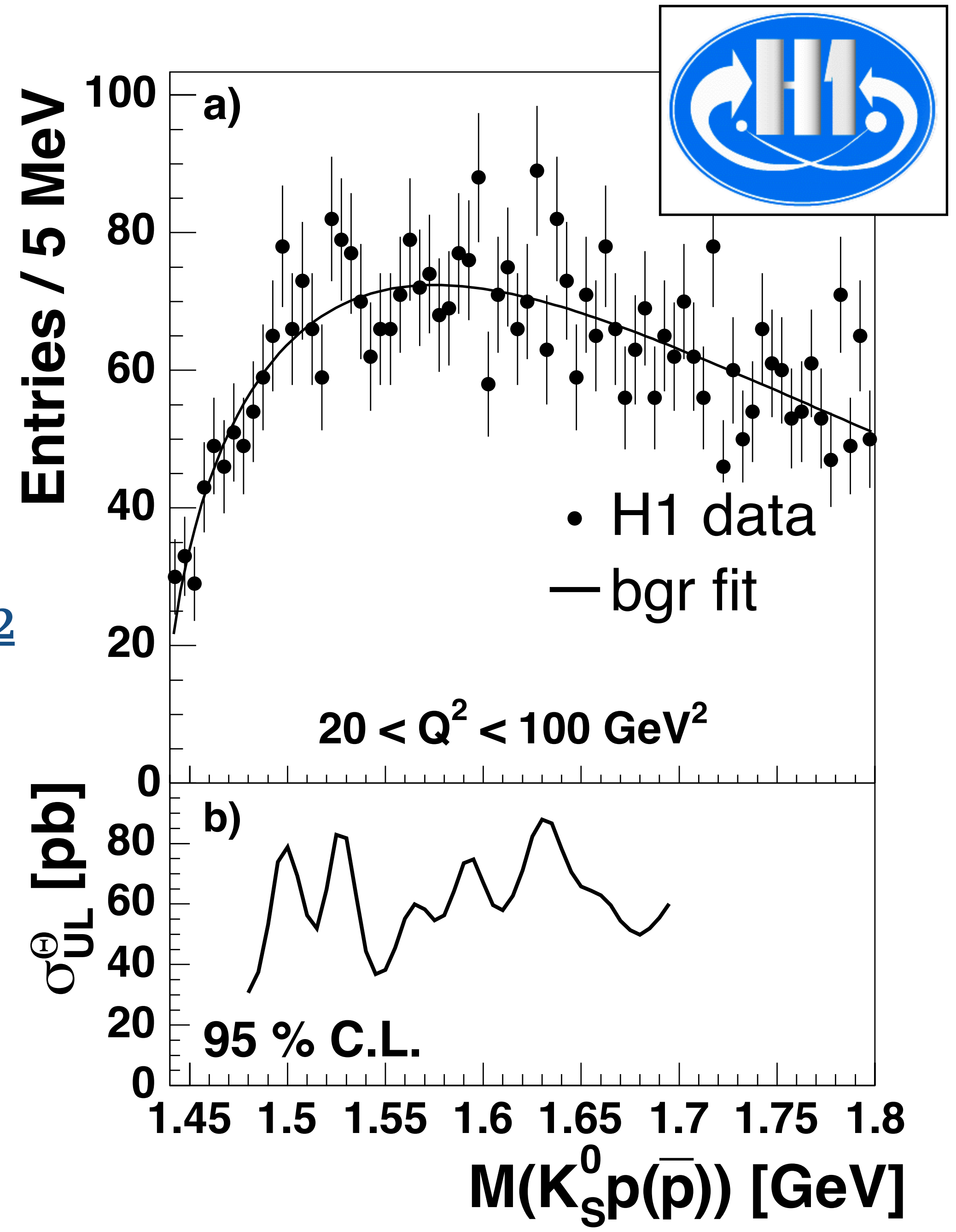
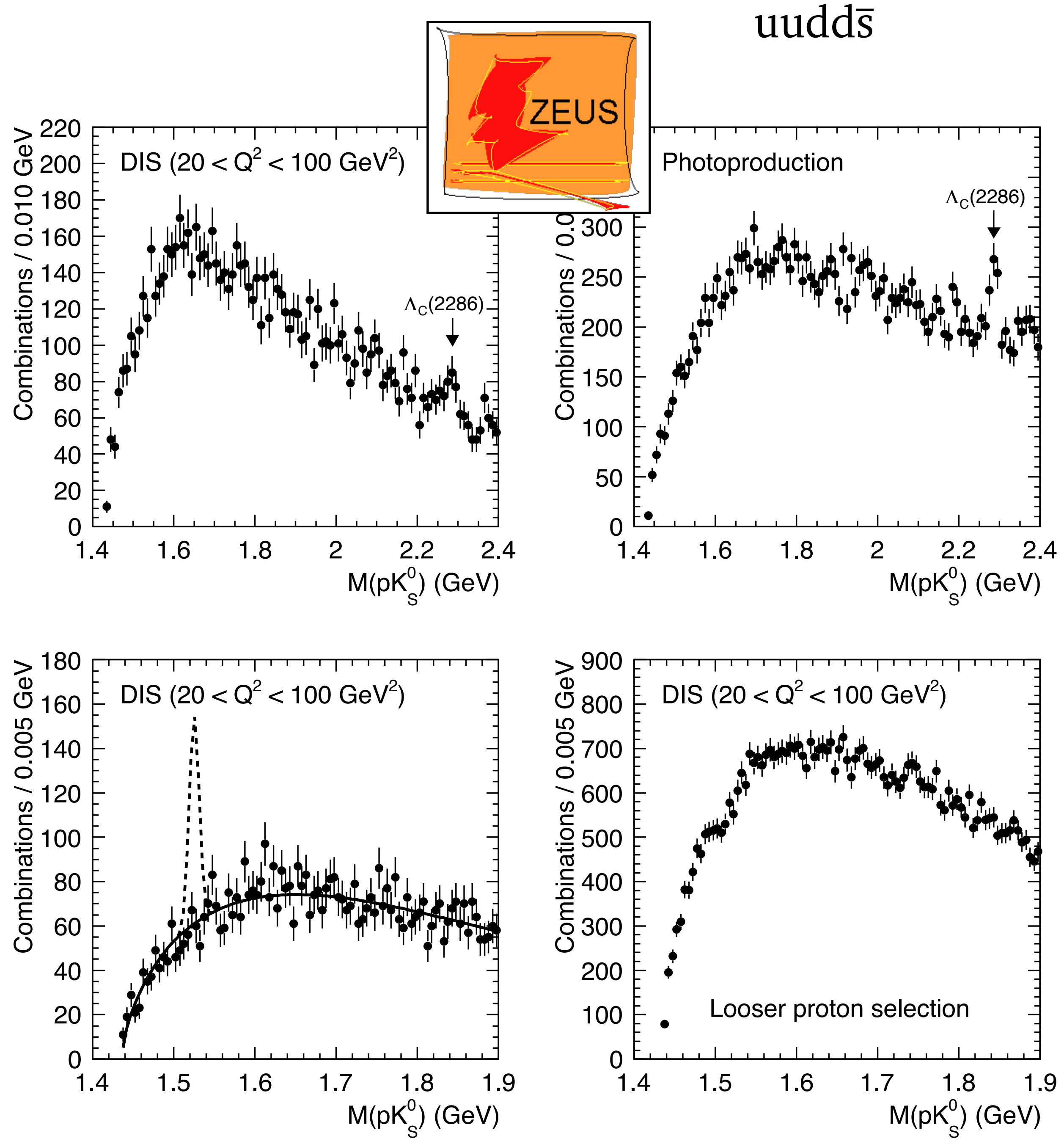
Phys. Lett. B 639 (2006) 202



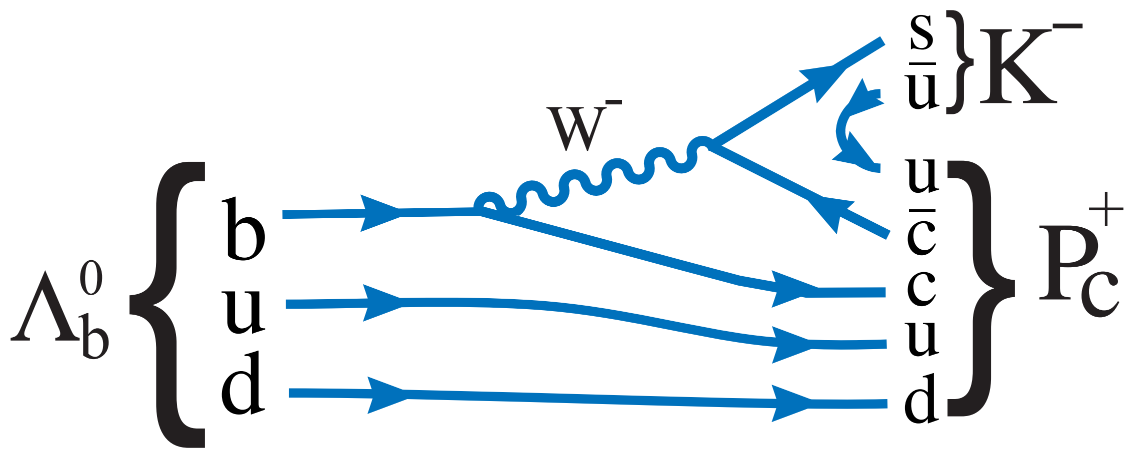


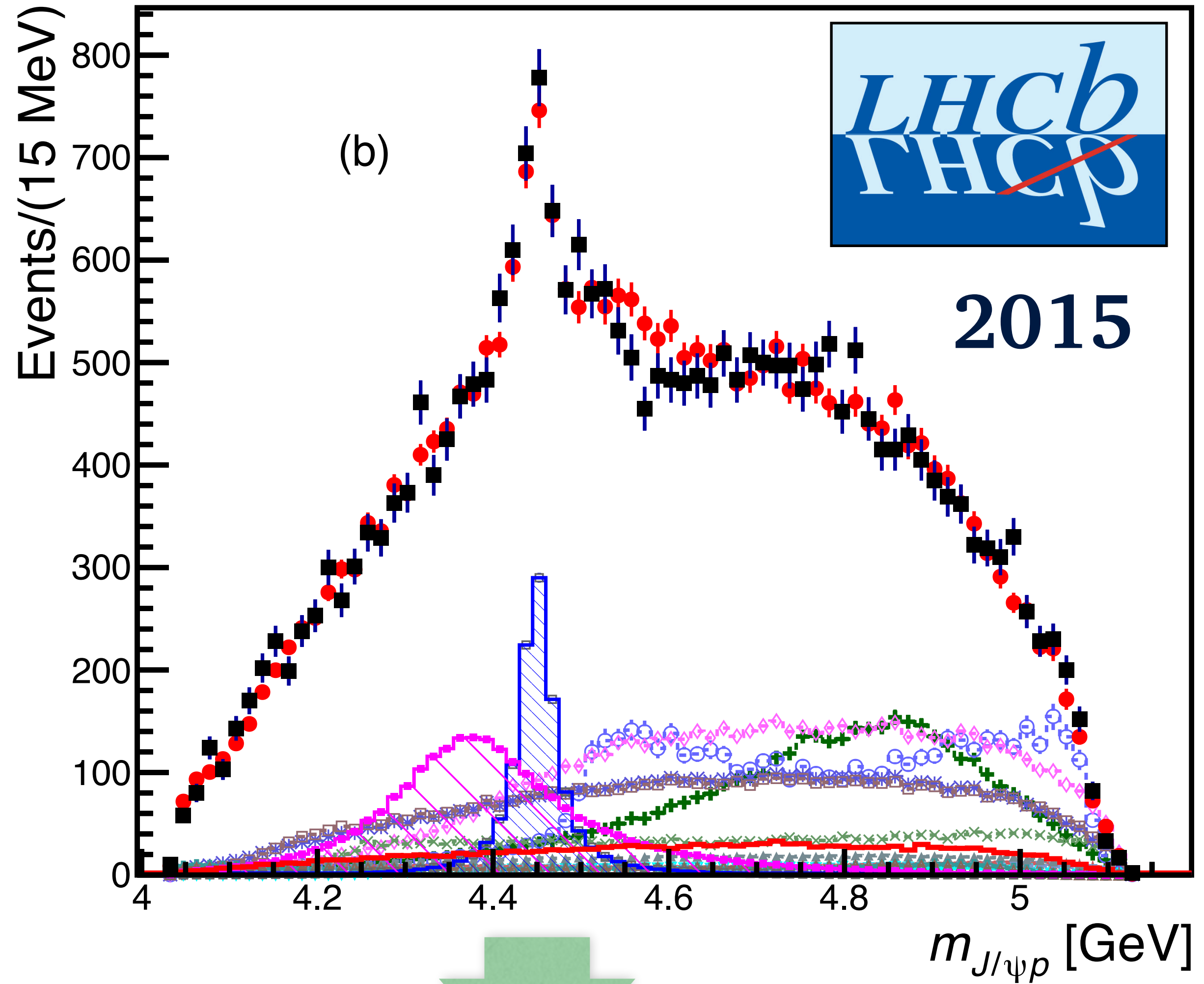
No Θ^+ peak observed by **ZEUS** in **HERA II** data

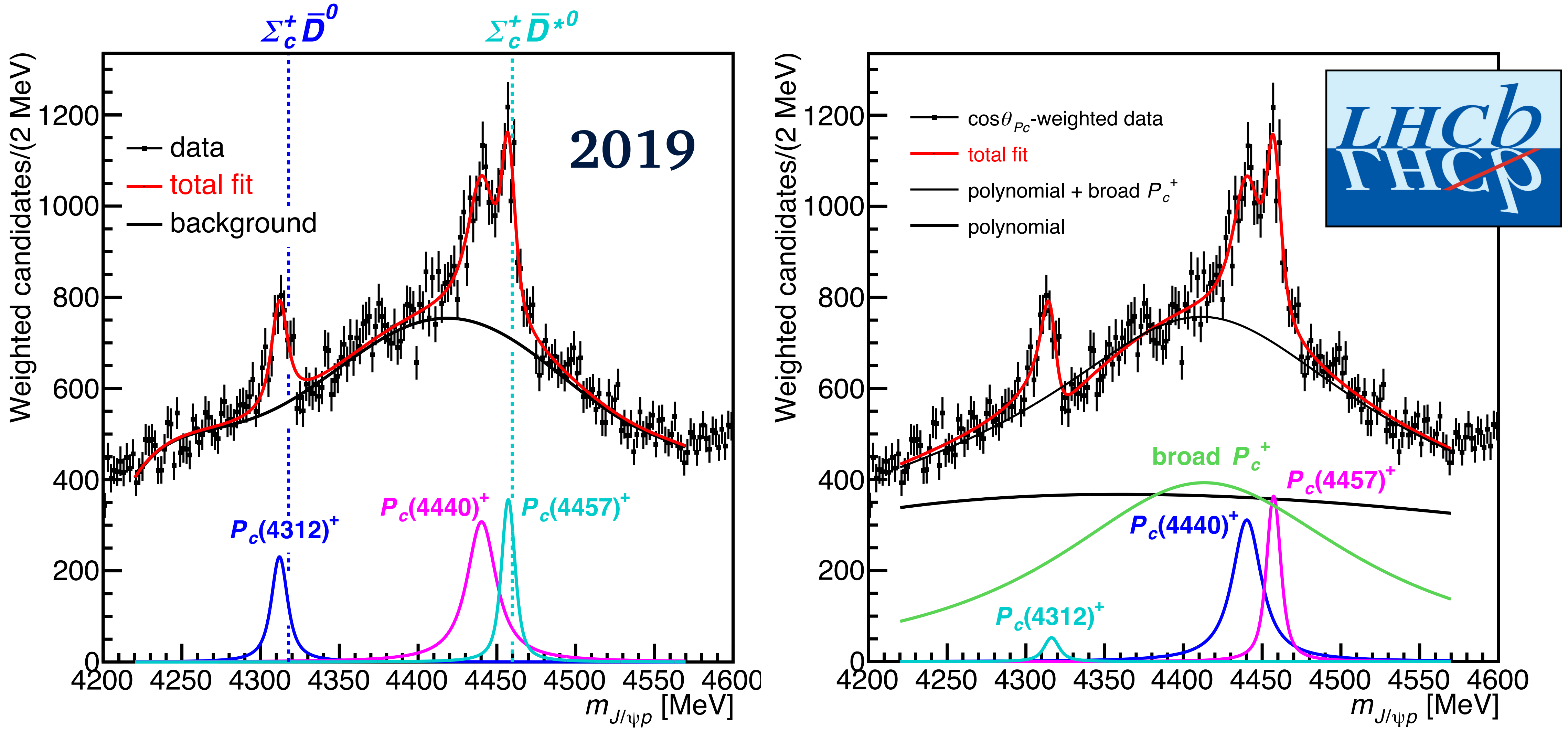
Phys. Lett. B 759 (2016) 446

2015 - present:

Discovery of the $\mathbf{P^+_c}$ ($c\bar{c}uud$) pentaquark states at LHCb

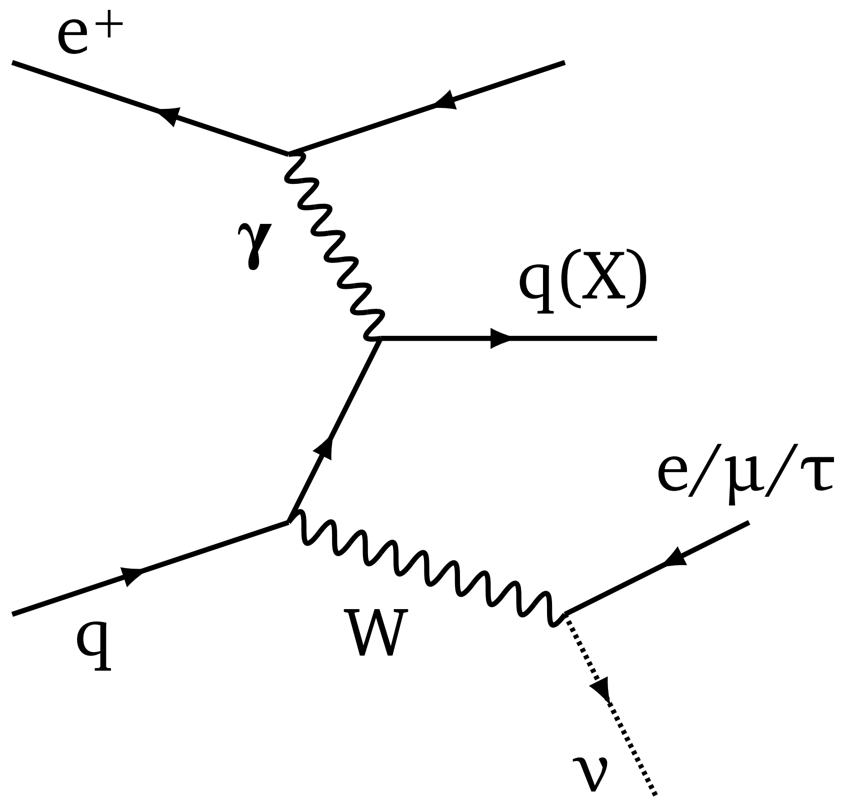




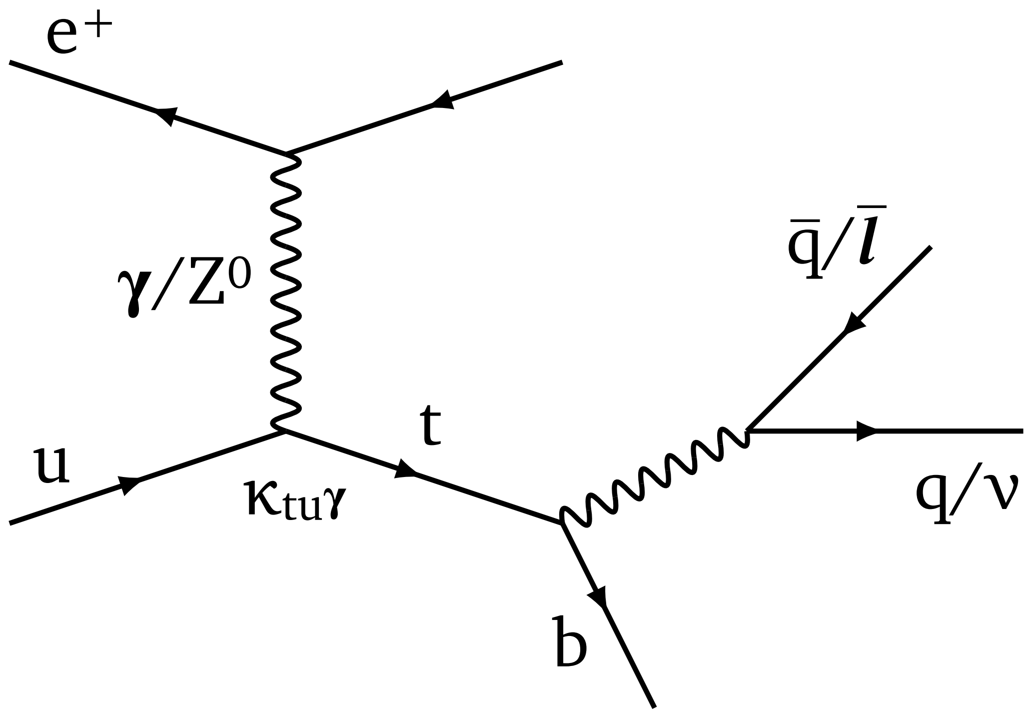


Isolated Leptons

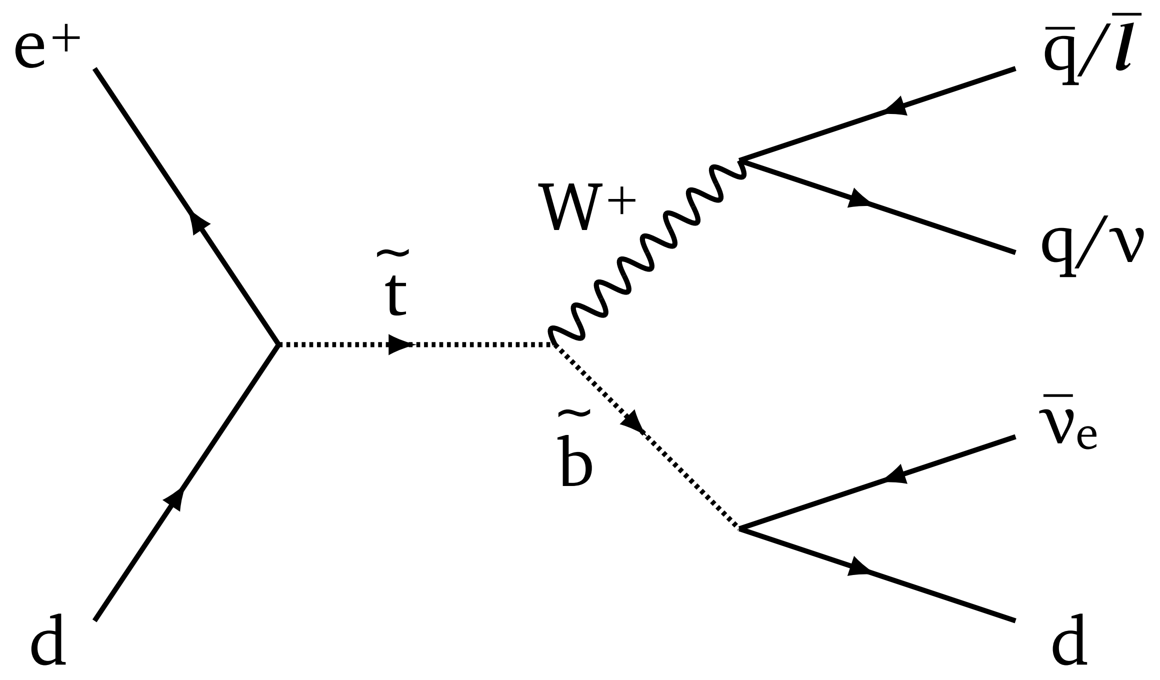
In case of events excess, some of the possible interpretations:



Isolated high-P_T lepton,
high P_T^{miss} and P_T^X



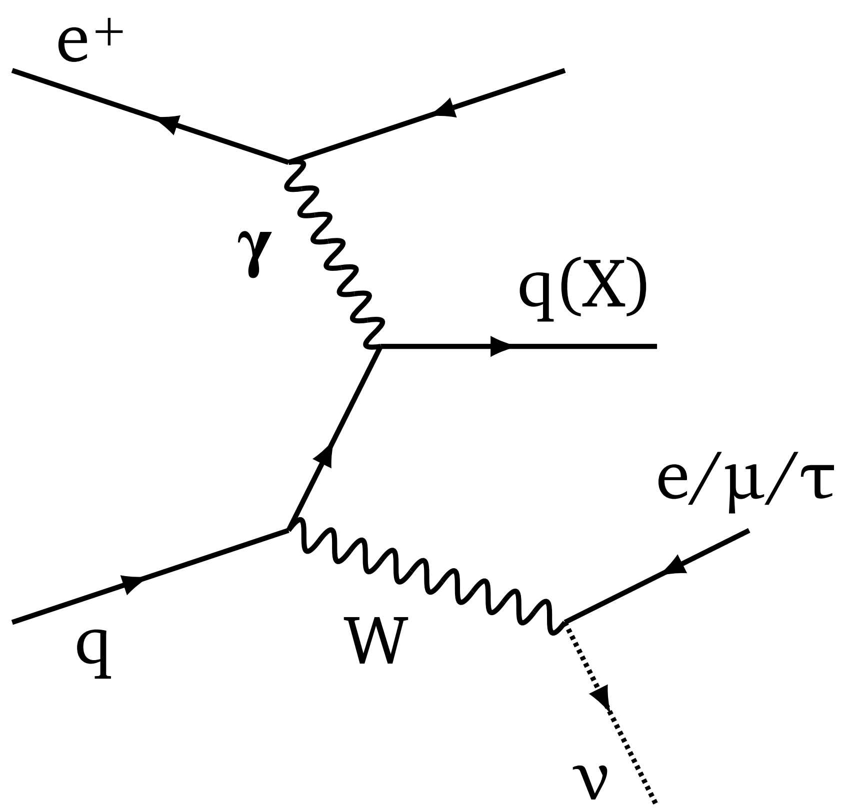
anomalous single-top production



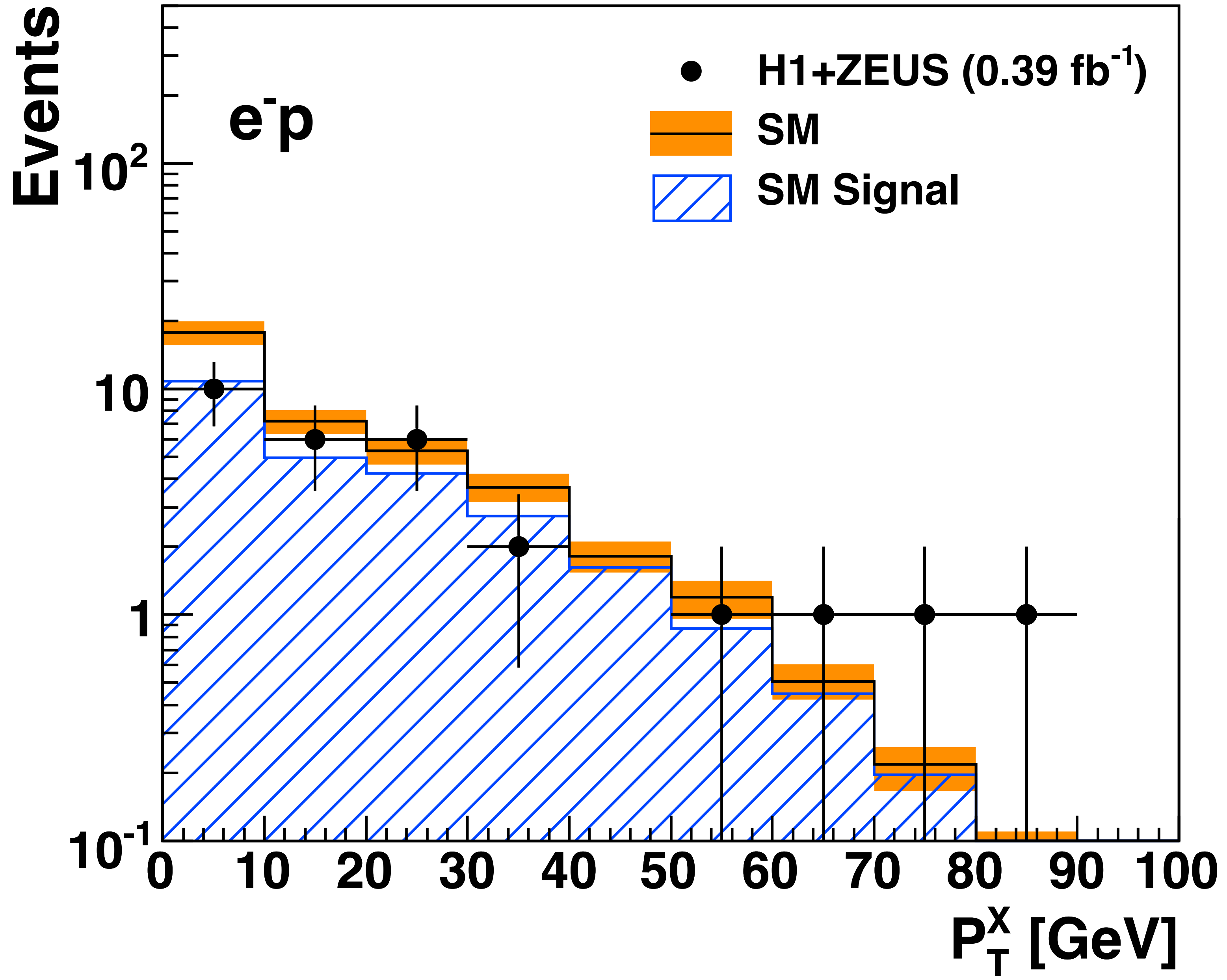
stop production in the
R-parity breaking SUSY

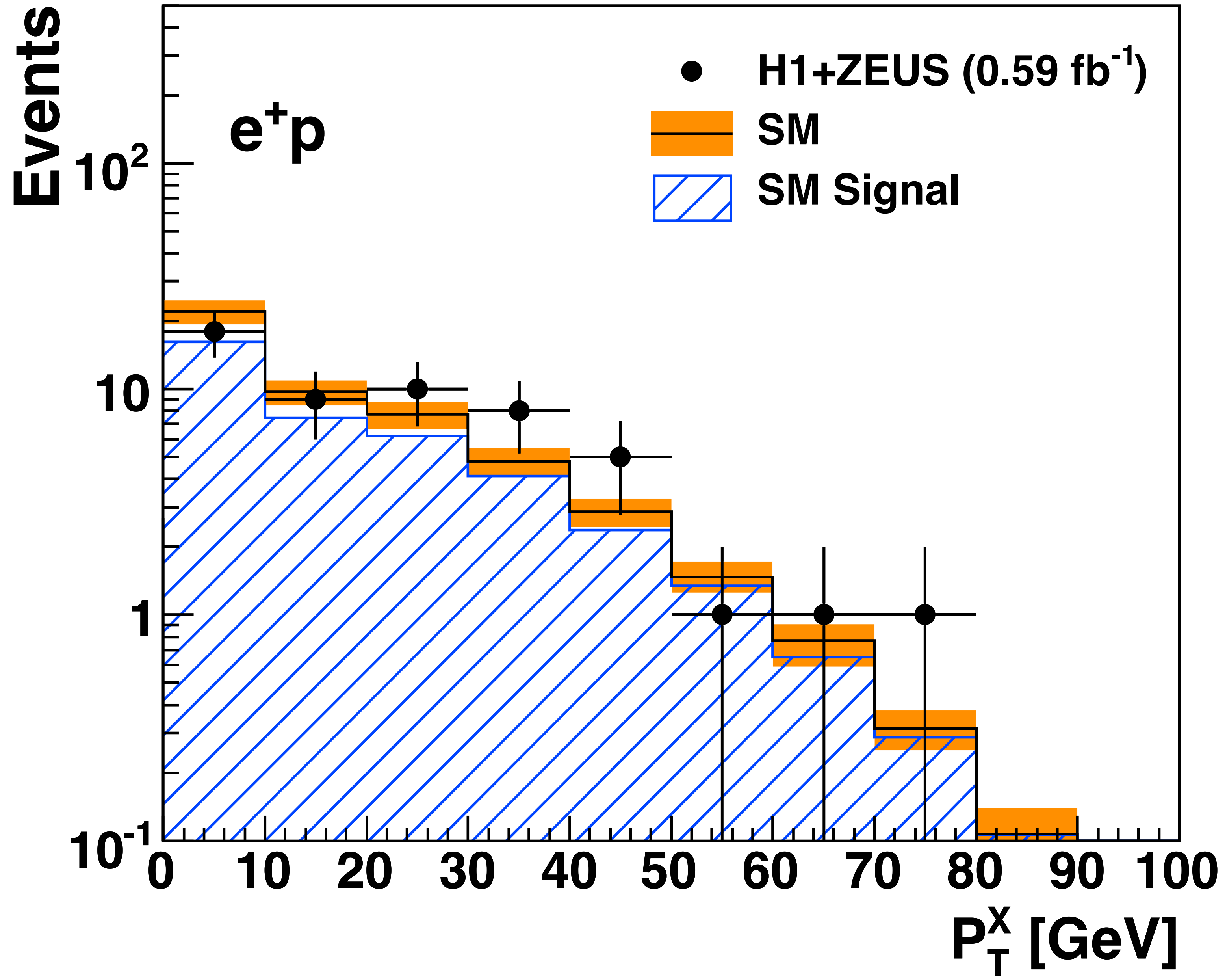
Isolated Leptons

Bin-to-bin combination of the data from H1 and ZEUS - **1 fb^{-1}** of data.



Isolated high-P_T lepton, high P_T^{miss} and P_T^X



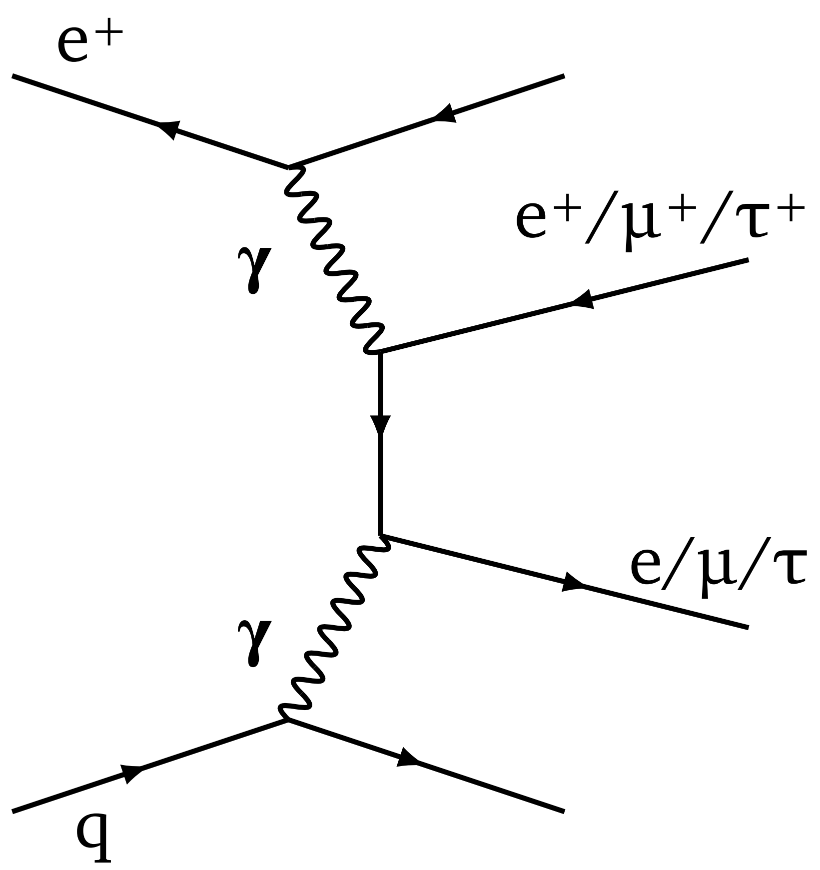


JHEP 1003 (2010) 035

In total, **23** events with P_T^X > 25 GeV observed, **14.0 ± 1.9** expected.

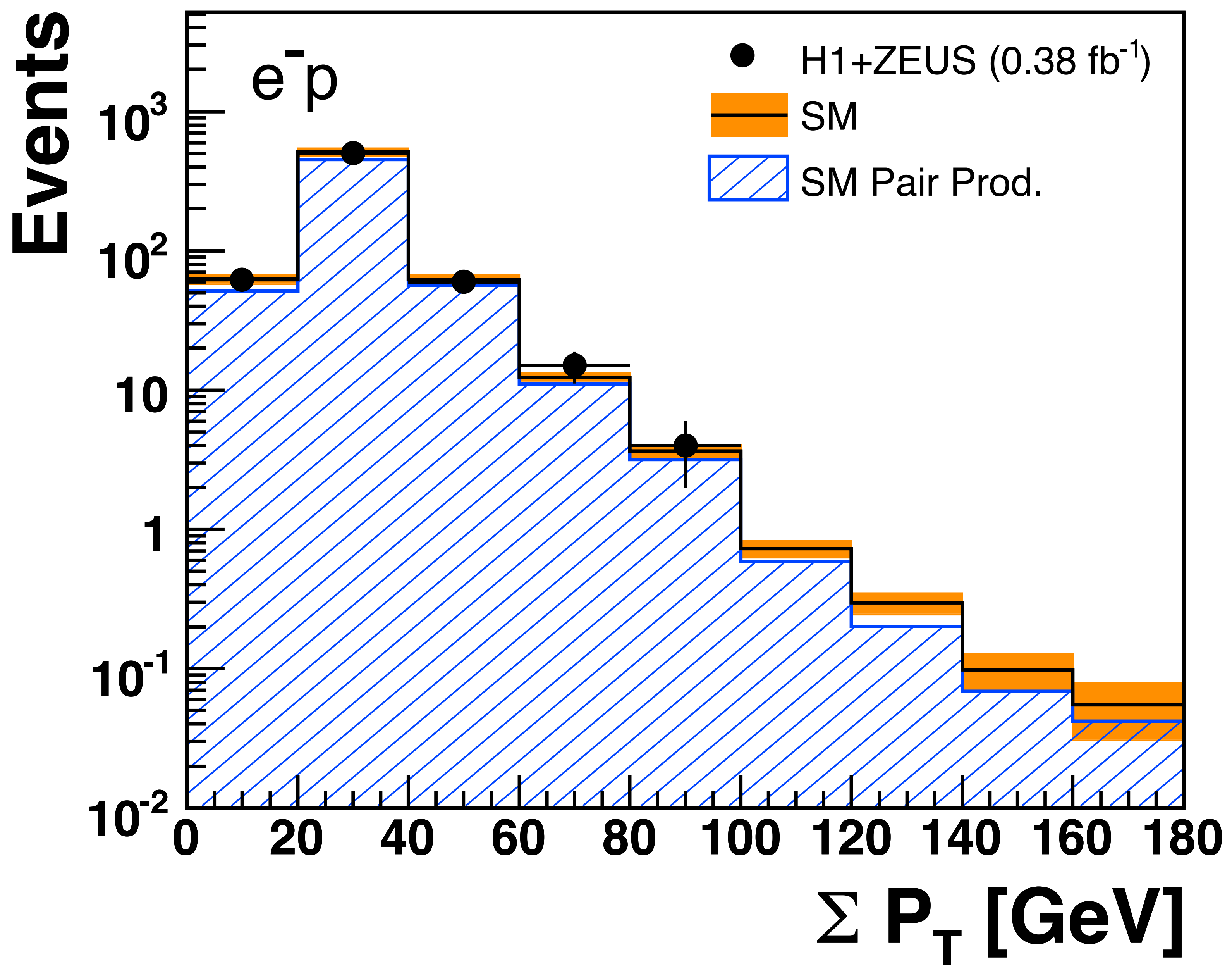
Multi-Leptons

Bin-to-bin combination of the data from H1 and ZEUS - **1 fb^{-1}** of data.

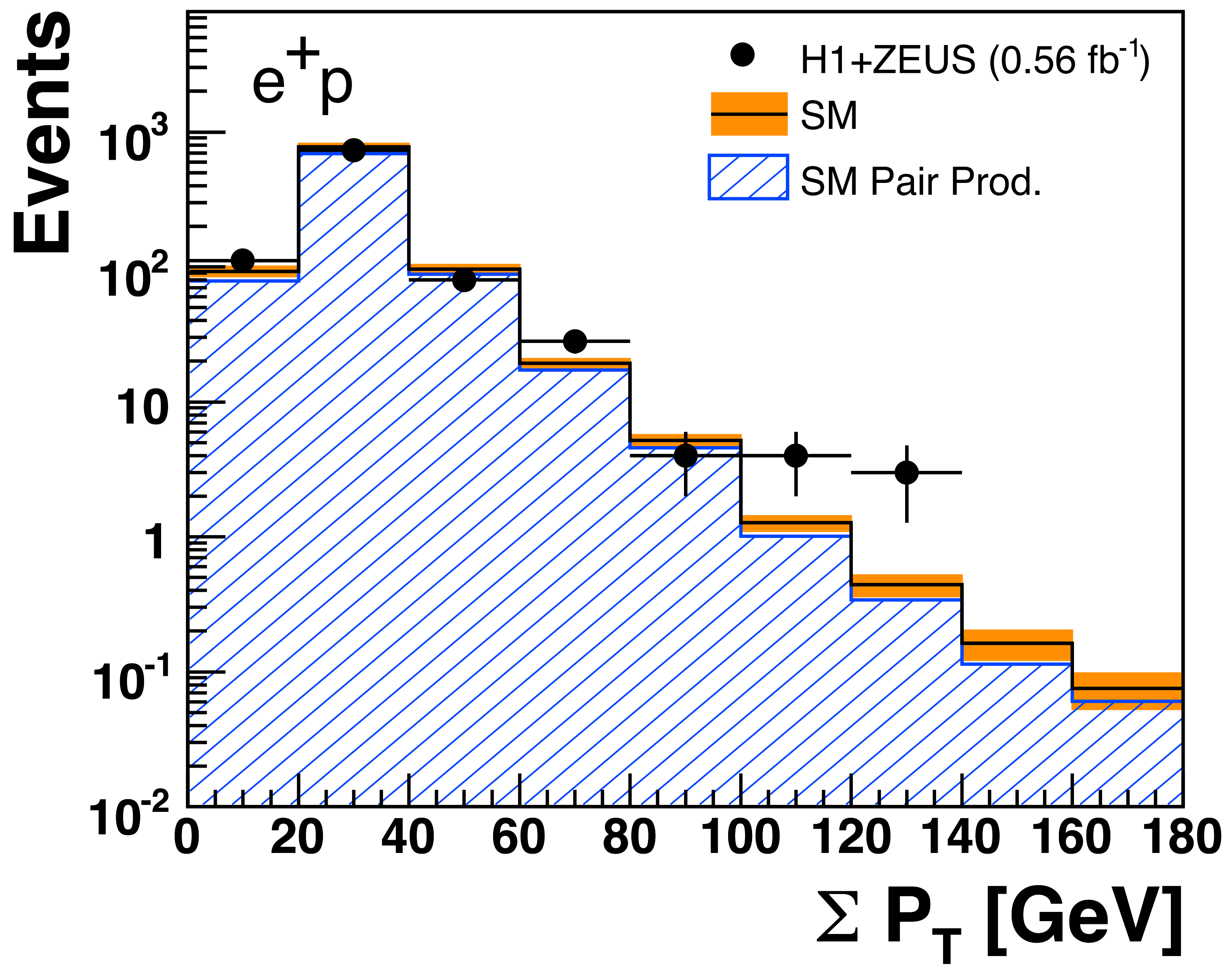


At least 2 high-P_T leptons

JHEP 0910 (2009) 013

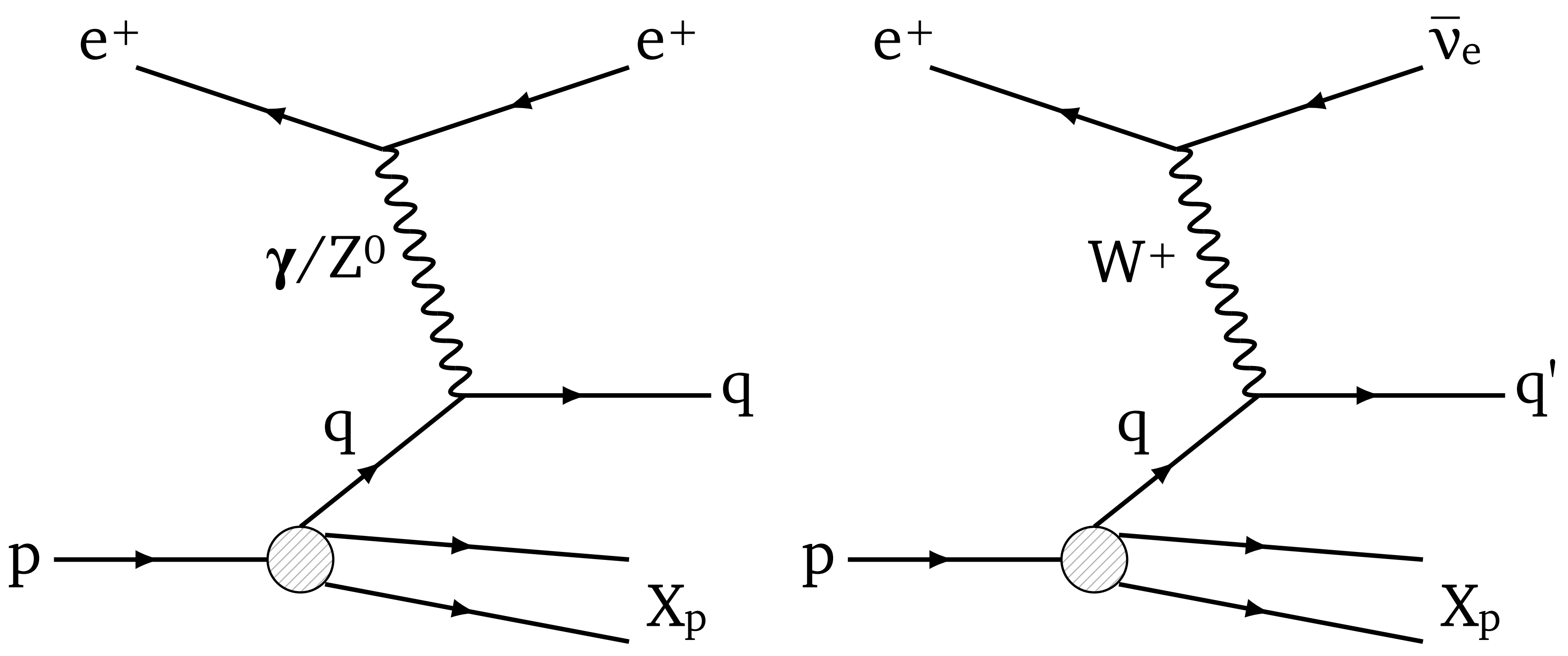


0 events with $\sum P_T$ > 100 GeV observed,
1.19 ± 0.12 expected.



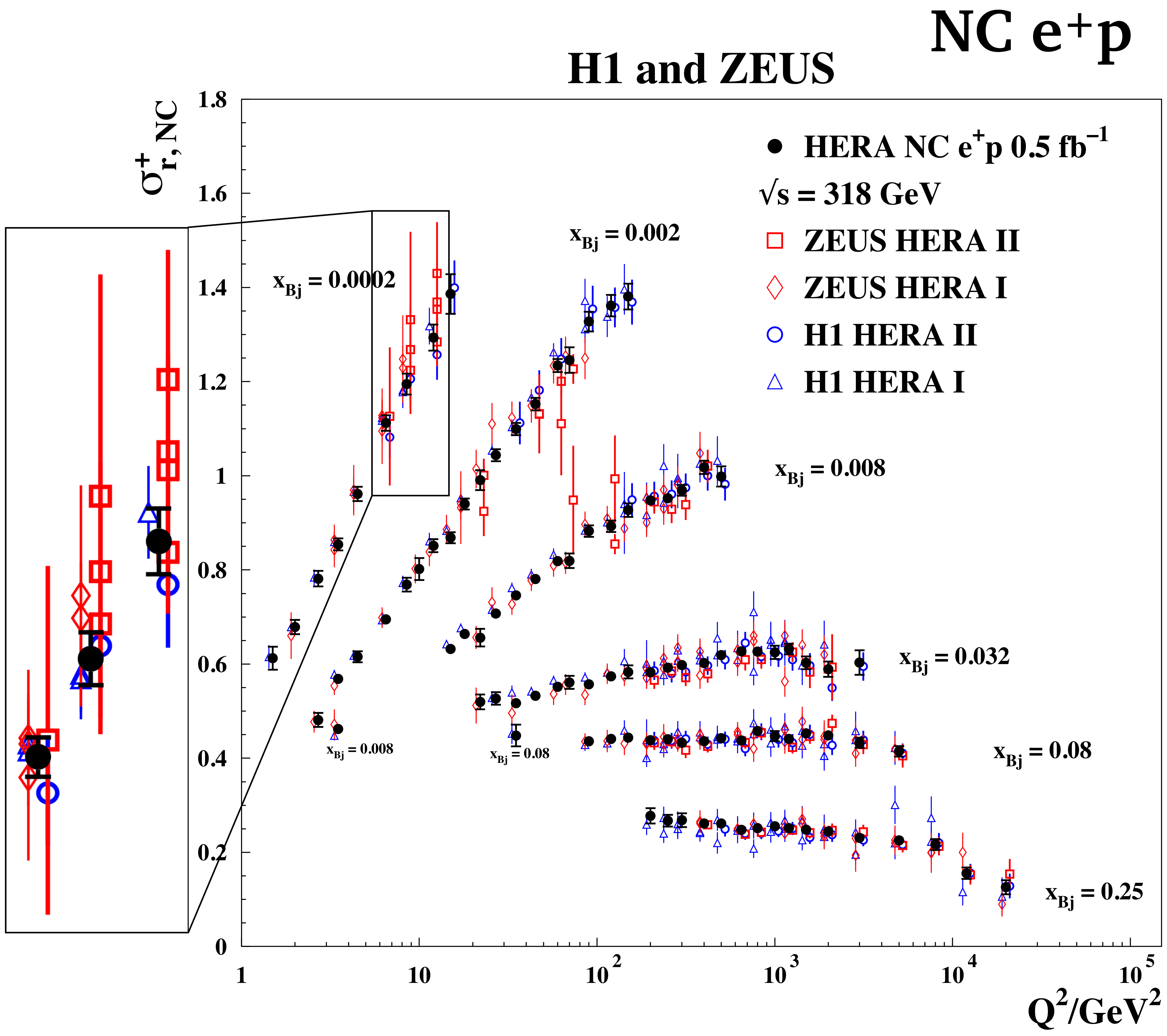
7 events with $\sum P_T$ > 100 GeV observed,
1.94 ± 0.17 expected.

HERA inclusive DIS data combination



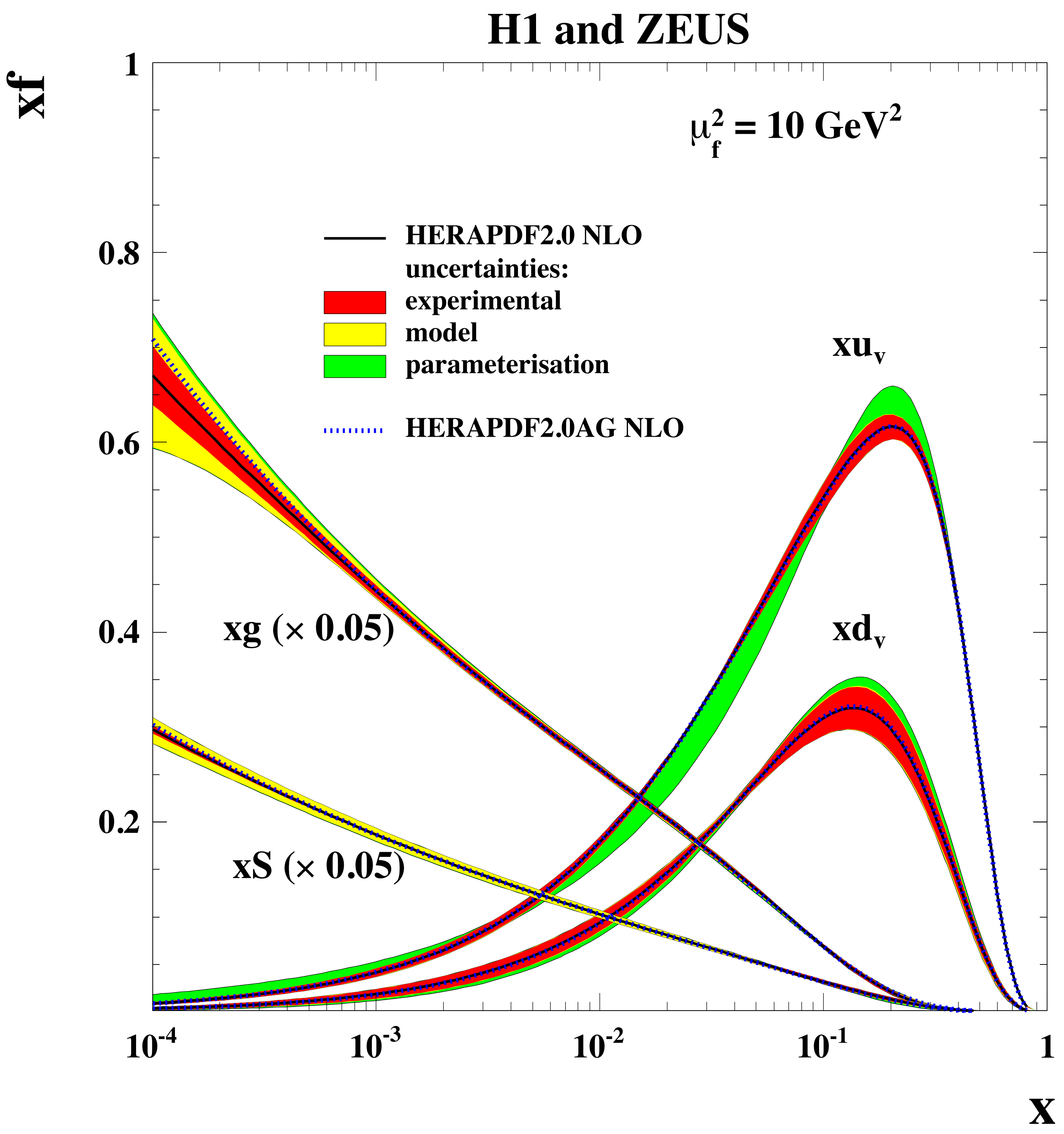
NC e+p **CC e+p**

- 2927 data point combined to 1307
- up to 8 data points combined to 1
- impressive improvement of precision due to:
  - increased statistics
  - better understanding of systematics
  - cross-calibration of the data from two experiments



[Eur. Phys. J. C75 (2015), No. 12, 580]

QCD analysis of the combined DIS data



Parton Density Functions

Parameterised at the starting scale of $Q^2_0 = 1.9$ GeV^2:

$$xg(x) = \boxed{A_g} x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{\boxed{C'_g}}$$

$$xu_v(x) = \boxed{A_{u_v}} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right)$$

$$xd_v(x) = \boxed{A_{d_v}} x^{B_{d_v}}(1-x)^{C_{d_v}}$$

$$x\bar{U}(x) = \boxed{A_{\bar{U}}} x^{\boxed{B_{\bar{U}}}}(1-x)^{C_{\bar{U}}}\left(1 + D_{\bar{U}}x\right)$$

$$x\bar{D}(x) = \boxed{A_{\bar{D}}} x^{\boxed{B_{\bar{D}}}}(1-x)^{C_{\bar{D}}}$$

fixed or calculated by the sum-rules

set equal

Evolve to any $Q^2 > Q^2_0$ with DGLAP.

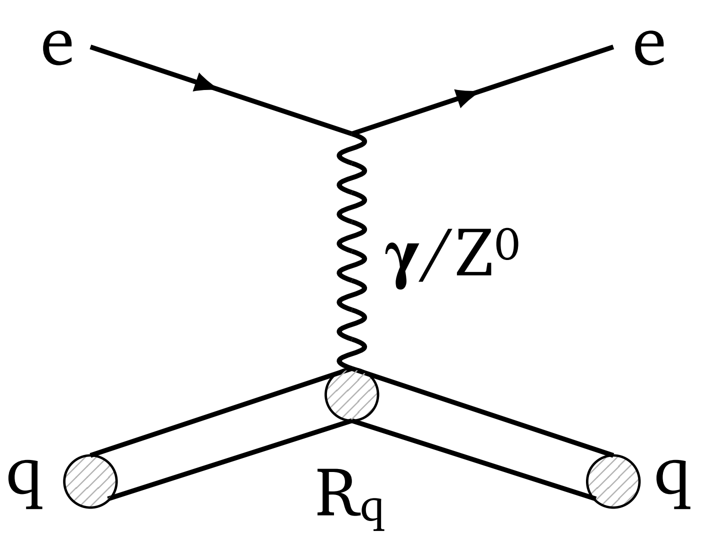
Eur. Phys. J. C75 (2015), No. 12, 580

- BSM signal in the data could affect the PDF fit and result in **biased PDFs**.
- This could affect all available high-precision PDFs (MMHT2014, NNPDF 3.0, etc.) - they all include HERA DIS data in the fit.
- Proper procedure for a BSM analysis of the HERA data - global **QCD analysis which includes a possible contribution from BSM** processes.

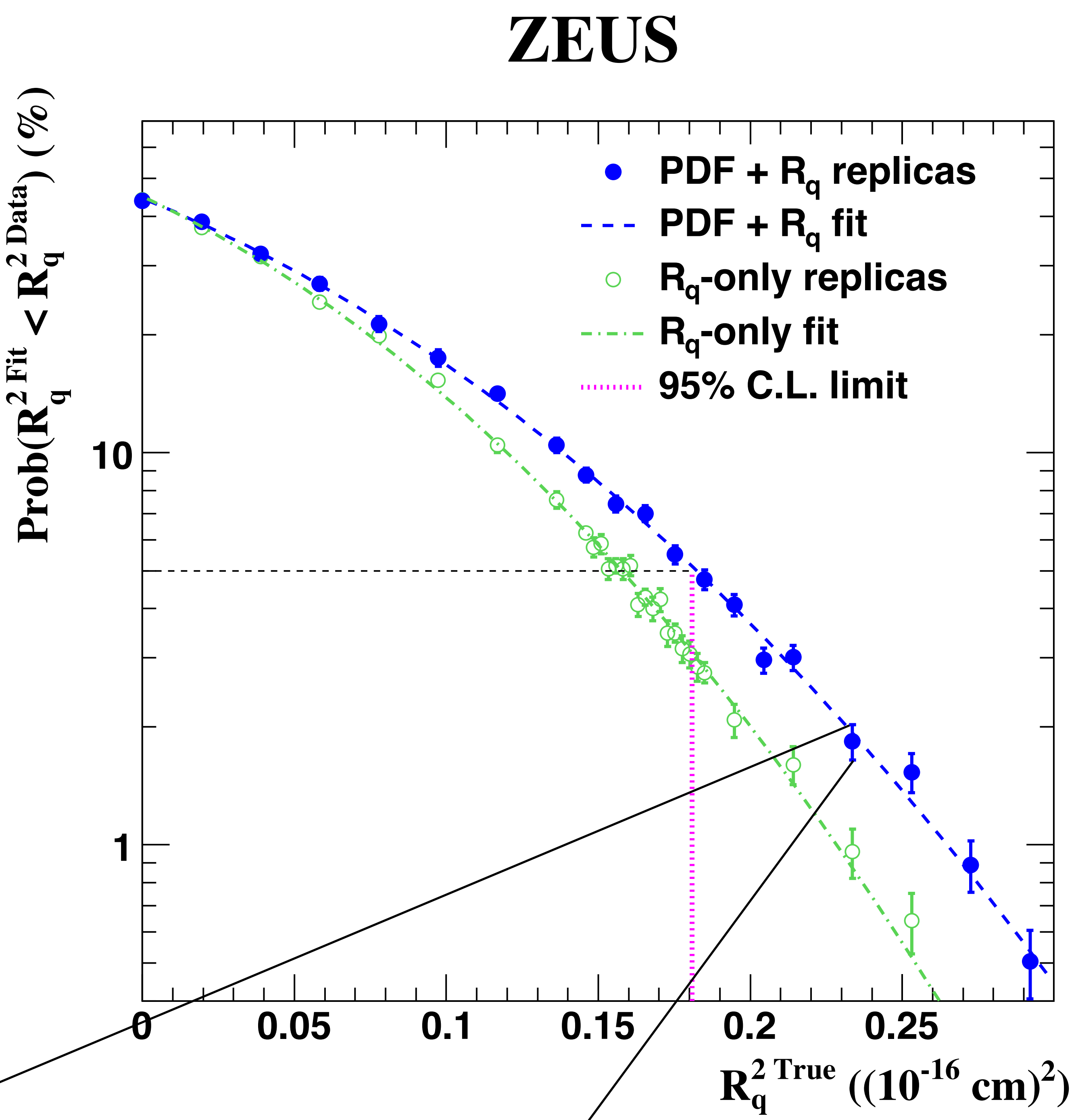
Simultaneous PDF + R_q analysis

Wide kinematic range of the HERA data allows determination of PDFs simultaneously with BSM searches.

For example - quark form-factor:

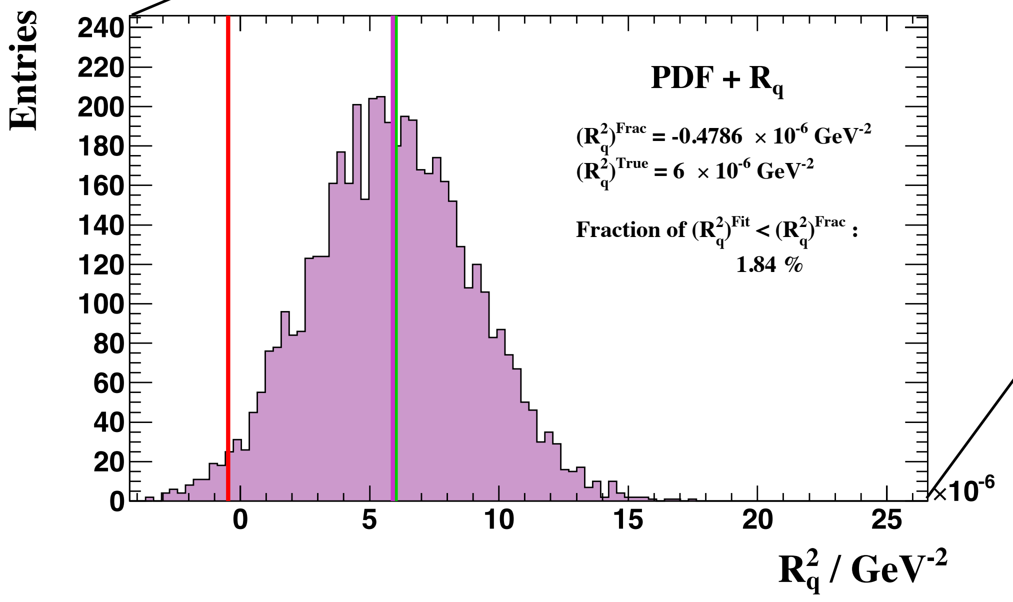


$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \times \left(1 - \frac{R_q^2}{6} Q^2\right)^2$$



Frequentist analysis - generate MC replicas and simultaneously fit PDFs and Rq:

$$\mu^i = \left[m_0^i + \sqrt{\delta_{i,stat}^2 + \delta_{i,uncor}^2} \cdot \mu_0^i \cdot r_i\right] \cdot \left(1 + \sum_j \gamma_j^i \cdot r_j\right)$$



Phys. Lett. B757 (2016), 468-472

95% C.L. limits (H1 + ZEUS data, 1 fb^{-1}):

$-[0.47 \cdot 10^{-16}\text{ cm}]^2 \leq R_q^2 \leq [0.43 \cdot 10^{-16}\text{ cm}]^2$

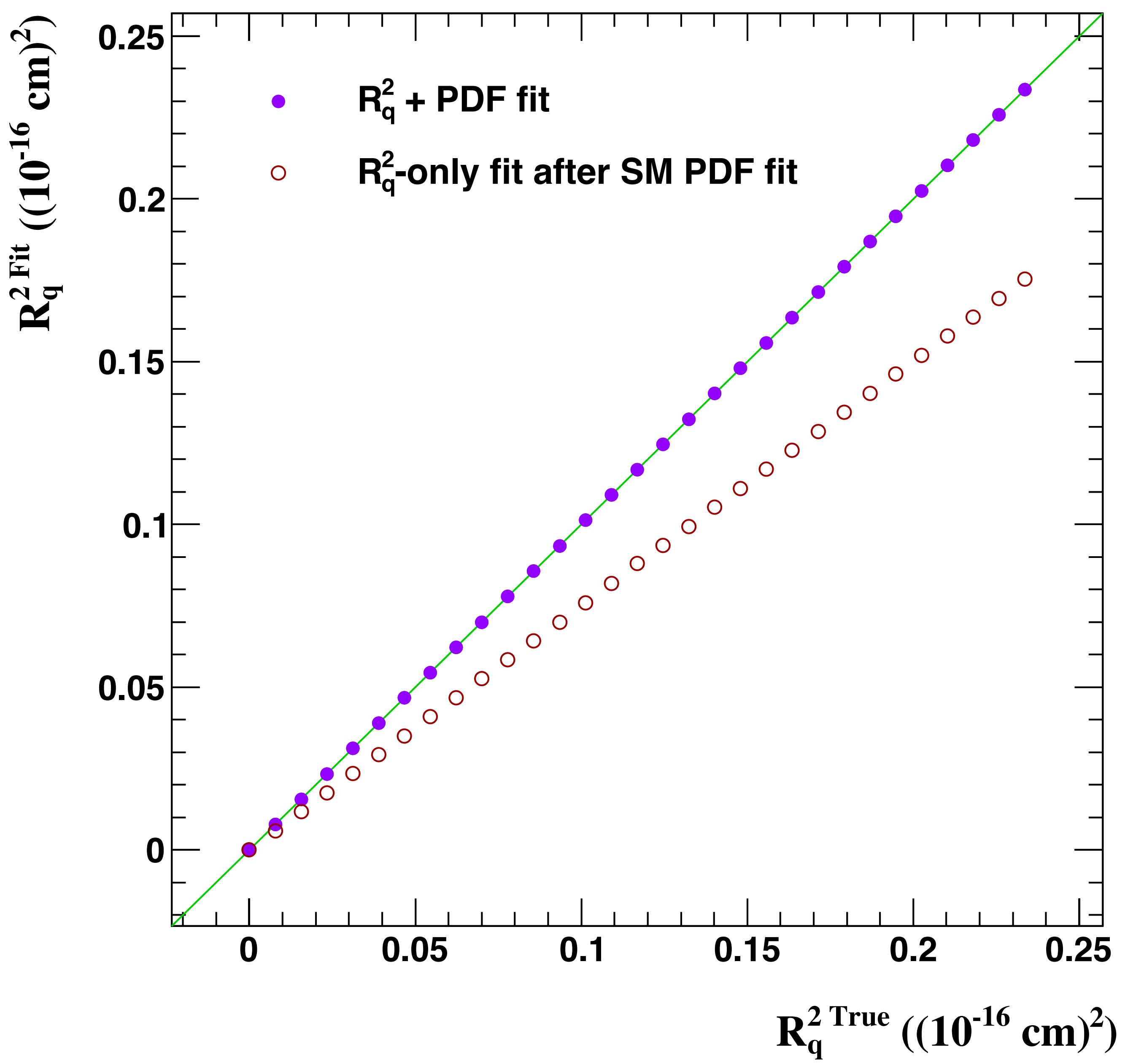
Previous results:

H1 (446 pb^{-1}):	ZEUS (128 pb^{-1}):
$R_q \leq 0.65 \cdot 10^{-16}$ cm	$R_q \leq 0.85 \cdot 10^{-16}$ cm
Phys. Lett. B705 (2011) 52	Phys. Lett. B591 (2004) 23

Conclusions from simultaneous analysis

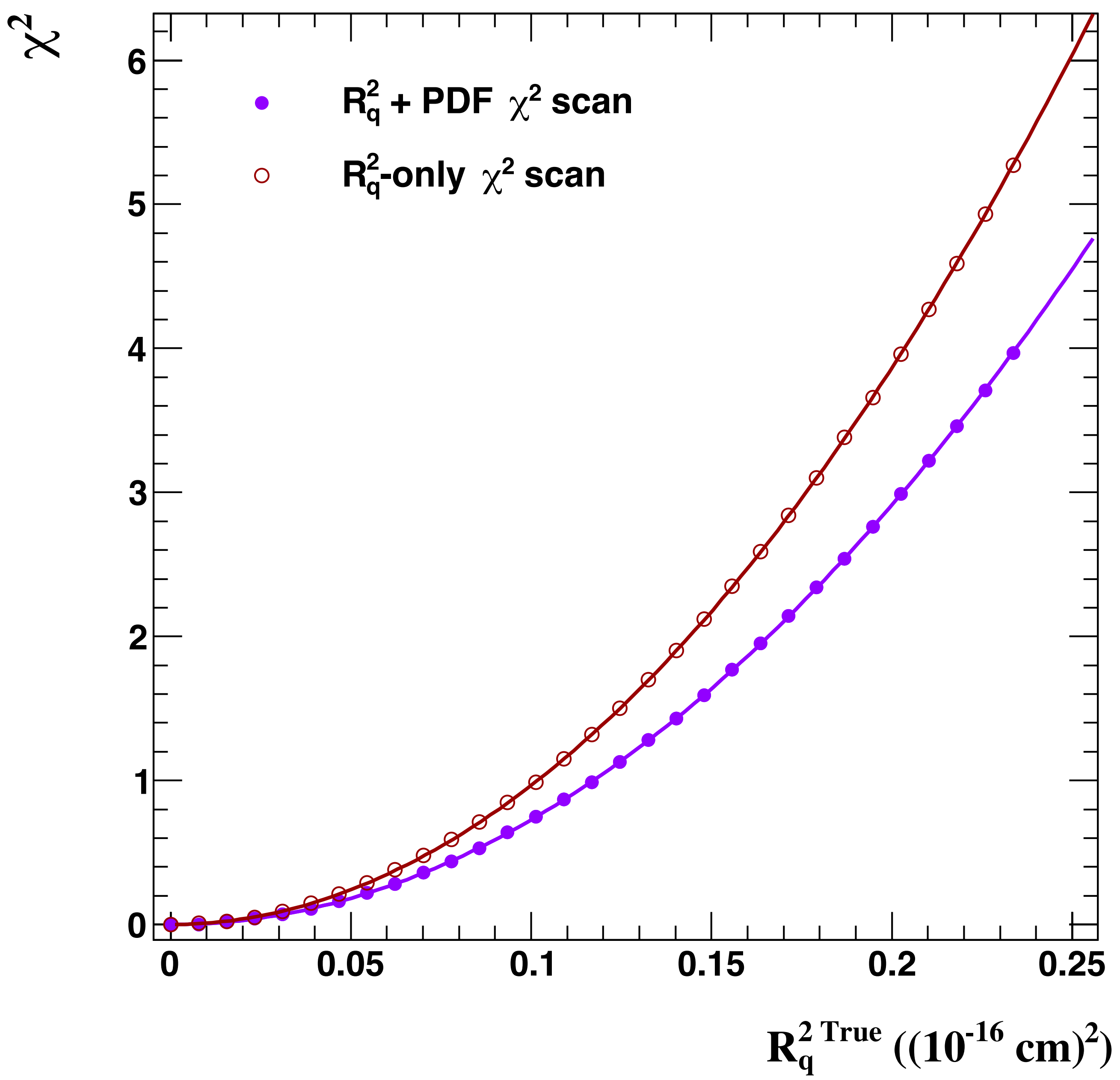
- BSM signal in the data affects the PDF fit and results in **biased PDFs**.
- Use of the **biased PDFs** in the BSM analysis results in **overestimated limits**.

Pseudodata generated for values of $\mathbf{R^2_q = R^2_q{}^{True}}$



$\mathbf{R^2_q}$**+PDF** procedure provides unbiased results of $\mathbf{R^2_q{}^{Fit}}$

Pseudodata generated for value of $\mathbf{R^2_q = 0}$

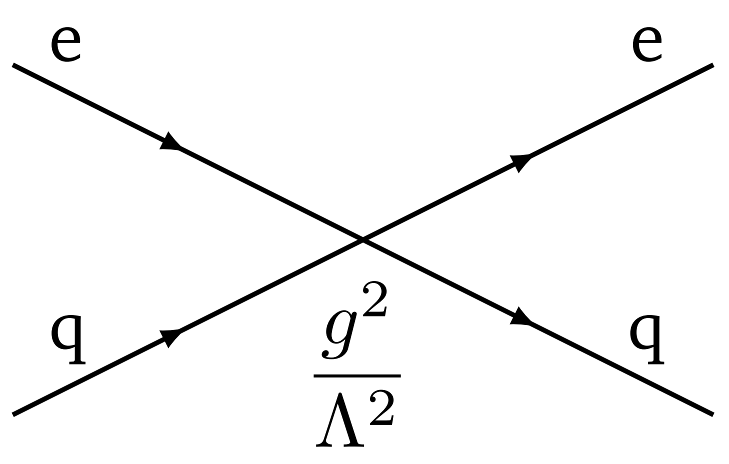


$\mathbf{R^2_q}$**-only** procedure results in too strong limits

General contact interactions and leptoquarks

Low-energy effects due to physics at much higher energy scales can be described with the four-fermion contact interactions (CI):

$$\mathcal{L}_{\mathrm{CI}} = \sum_{\substack{k,j=L,R \\ q=u,d,s,c,b}} \eta_{kj}^{eq} (\bar{e}_k \gamma^{\mu} e_k)(\bar{q}_j \gamma_{\mu} q_j)$$



$$\eta_{kj}^{eq} = \epsilon_{kj}^{eq} \frac{g^2}{\Lambda^2}$$

$$\epsilon_{kj}^{eq} = \pm 1; 0$$

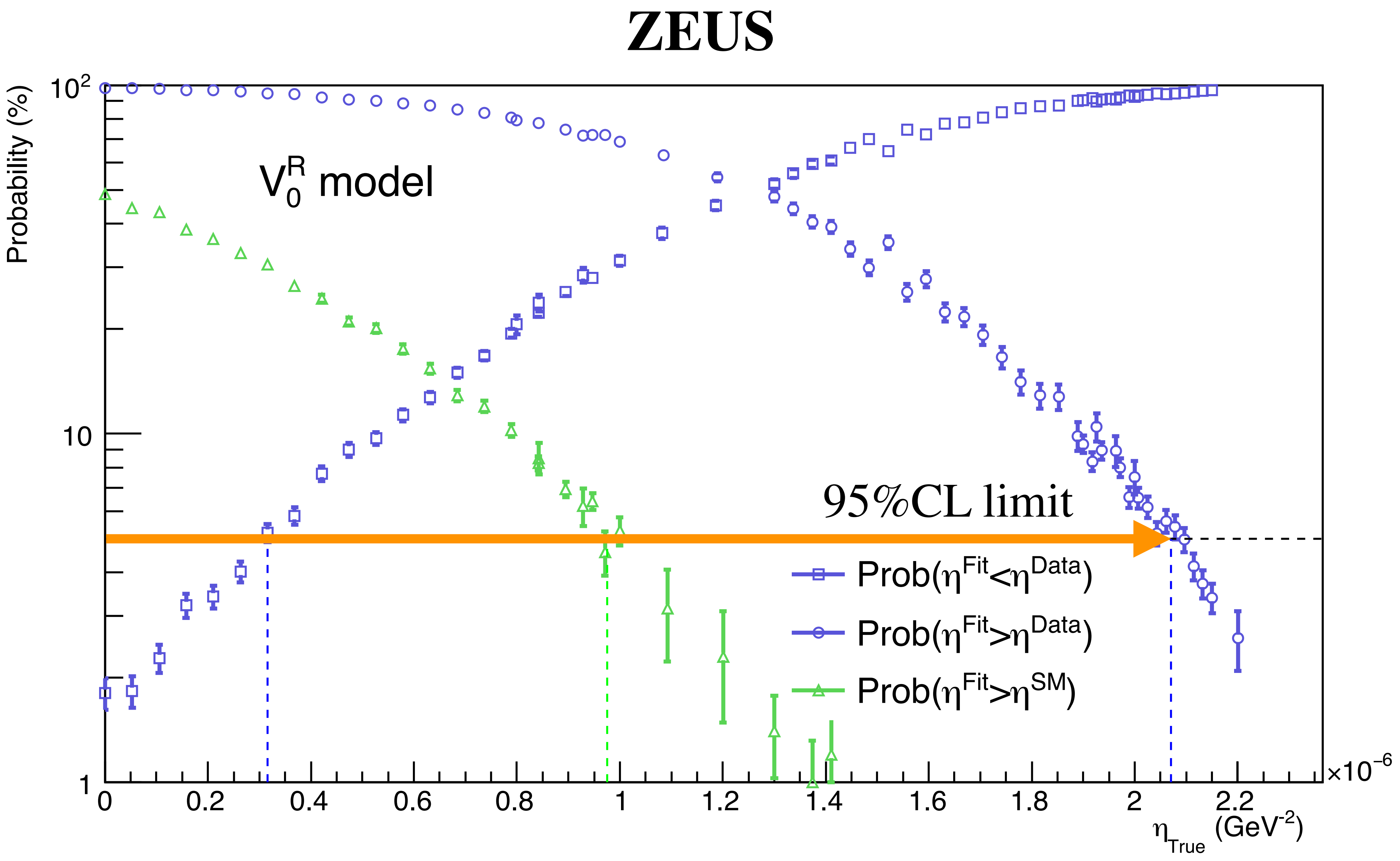
All up- or down-type quarks were assumed to have the same contact-interaction couplings:

$$\eta_{kj}^{eu} = \eta_{kj}^{ec} = \eta_{kt}^{et}$$

$$\eta_{kj}^{ed} = \eta_{kj}^{es} = \eta_{kt}^{eb}$$

In the limit of heavy leptoquarks ($M_{LQ} \gg \sqrt{s}$), the effect of *s*- and *t*-channel LQ exchange is equivalent to a vector-type *eeqq* CI with the coupling of:

$$\eta_{kj}^{eq} = a_{kj}^{eq} \left(\frac{\lambda_{LQ}}{M_{LQ}} \right)^2$$



General contact interactions

Phys. Rev. D 99 (2019) 092006 Phys.Lett.B705 (2011) 52 Phys. Lett. B 591 (2004) 23-41

			95% C.L. lower coupling limits (TeV^{-2})							
			H1 + ZEUS data (1 fb^{-1})				H1(446 pb^{-1})		ZEUS (128 pb^{-1})	
Coupling structure		p_{SM}	Measured		Expected		Measured		Measured	
Model	[ε_{LL}, ε_{LR}, ε_{RL}, ε_{RR}]	(%)	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+
LL	[+1, 0, 0, 0]	7.0	12.8	4.5	5.9	6.3	4.0	4.2	1.7	2.7
RR	[0, 0, 0,+1]	5.9	14.7	4.4	5.7	6.1	3.9	4.4	1.8	2.7
LR	[0,+1, 0, 0]	34	4.7	5.5	5.7	6.3	3.7	4.8	2.4	3.6
RL	[0, 0,+1, 0]	42	5.0	5.3	5.6	6.5	3.8	4.8	2.7	3.5
VV	[+1,+1,+1,+1]	25	13.9	9.0	11.2	11.4	7.2	5.6	6.2	5.4
AA	[+1,−1,−1,+1]	0.6	15.7	4.2	7.9	7.8	5.1	4.4	4.7	4.4
VA	[+1,−1,+1,−1]	2.5 (5.8)	3.6	3.5	4.2	4.2	3.6	3.8	3.3	3.2
X1	[+1,−1, 0, 0]	0.4	–	3.2	5.4	5.5			3.6	2.6
X2	[+1, 0,+1, 0]	24	10.4	6.4	7.8	8.3			3.9	4.0
X3	[+1, 0, 0,+1]	7.3	17.9	6.2	8.3	8.7	5.1	5.3	3.7	3.6
X4	[0,+1,+1, 0]	39	7.2	7.5	8.0	8.6	4.8	5.4	5.1	4.8
X5	[0,+1, 0,+1]	27	9.5	6.4	7.7	7.7			4.0	4.0
X6	[0, 0,+1,−1]	0.3	3.1	–	5.3	5.5			2.5	3.5

For AA, VA, X1 and X6 models QCD+CI fits provide improved description of the data, with up to 2.7σ difference.

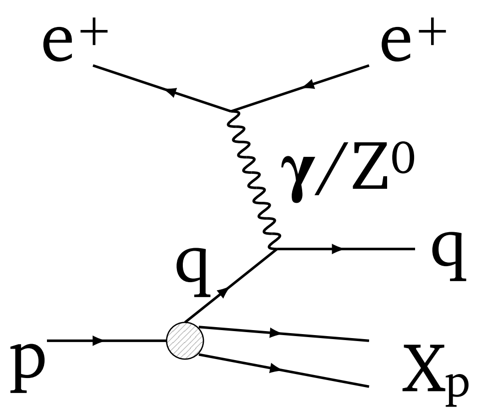
Leptoquarks

Phys. Rev. D 99 (2019) 092006 Phys.Lett.B705 (2011) 52 Phys. Lett. B 591 (2004) 23-41

			95% C.L. λ_{LQ}/M_{LQ} upper limits (TeV^{-1})			
		p_{SM}	H1 + ZEUS data (1 fb^{-1})		H1(446 pb^{-1})	ZEUS (128 pb^{-1})
Model	Coupling structure	(%)	Measured	Expected	Measured	Measured
S_o^L	$a_{LL}^{eu} = +\frac{1}{2}$	9.0	0.28	0.56	0.91	1.64
S_o^R	$a_{RR}^{eu} = +\frac{1}{2}$	5.5	1.03	0.72	0.91	1.79
$\widetilde{S}_o^R$	$a_{RR}^{ed} = +\frac{1}{2}$	1.8	–	1.71	2.44	3.70
$S_{\frac{1}{2}}^L$	$a_{LR}^{eu} = -\frac{1}{2}$	43	0.83	0.76	1.15	1.20
$S_{\frac{1}{2}}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = -\frac{1}{2}$	39	1.04	0.92	1.69	1.89
$\widetilde{S}_{\frac{1}{2}}^L$	$a_{LR}^{ed} = -\frac{1}{2}$	38	1.66	1.39	1.52	2.33
S_1^L	$a_{LL}^{ed} = +1, a_{LL}^{eu} = +\frac{1}{2}$	<0.01	1.18	0.62	1.41	1.92
V_o^L	$a_{LL}^{ed} = -1$	0.5	–	0.44	0.94	1.82
V_o^R	$a_{RR}^{ed} = -1$	1.8	1.47	0.99	1.10	2.13
$\widetilde{V}_o^R$	$a_{RR}^{eu} = -1$	5.5	0.18	0.53	0.74	1.15
$V_{\frac{1}{2}}^L$	$a_{LR}^{ed} = +1$	38	1.19	1.29	1.96	2.13
$V_{\frac{1}{2}}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = +1$	39	0.67	0.57	0.69	1.01
$\widetilde{V}_{\frac{1}{2}}^L$	$a_{LR}^{eu} = +1$	43	0.59	0.49	0.63	0.94
V_1^L	$a_{LL}^{ed} = -1, a_{LL}^{eu} = -2$	32	0.41	0.25	0.54	0.81

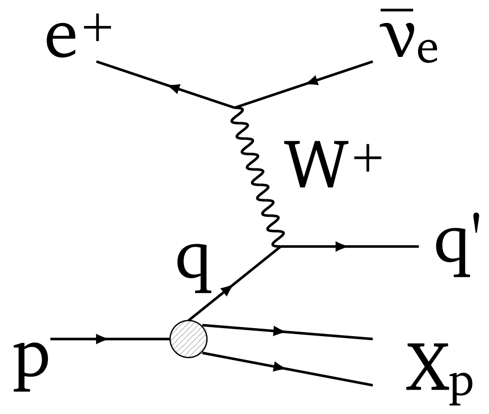
For S_1^L and V_0^R models the difference from SM predictions is about 4σ and 2σ, respectively.

BSM weak couplings



$$g_A^q = \sqrt{\boxed{\rho'_{NC,q}}\rho_{NC,q} I^3_{L,q}}$$

$$g_V^q = \sqrt{\boxed{\rho'_{NC,q}}\rho_{NC,q}}\left(I^3_{L,q} - 2Q_q \boxed{\kappa_{NC,q}} sin^2\theta_W\right)$$

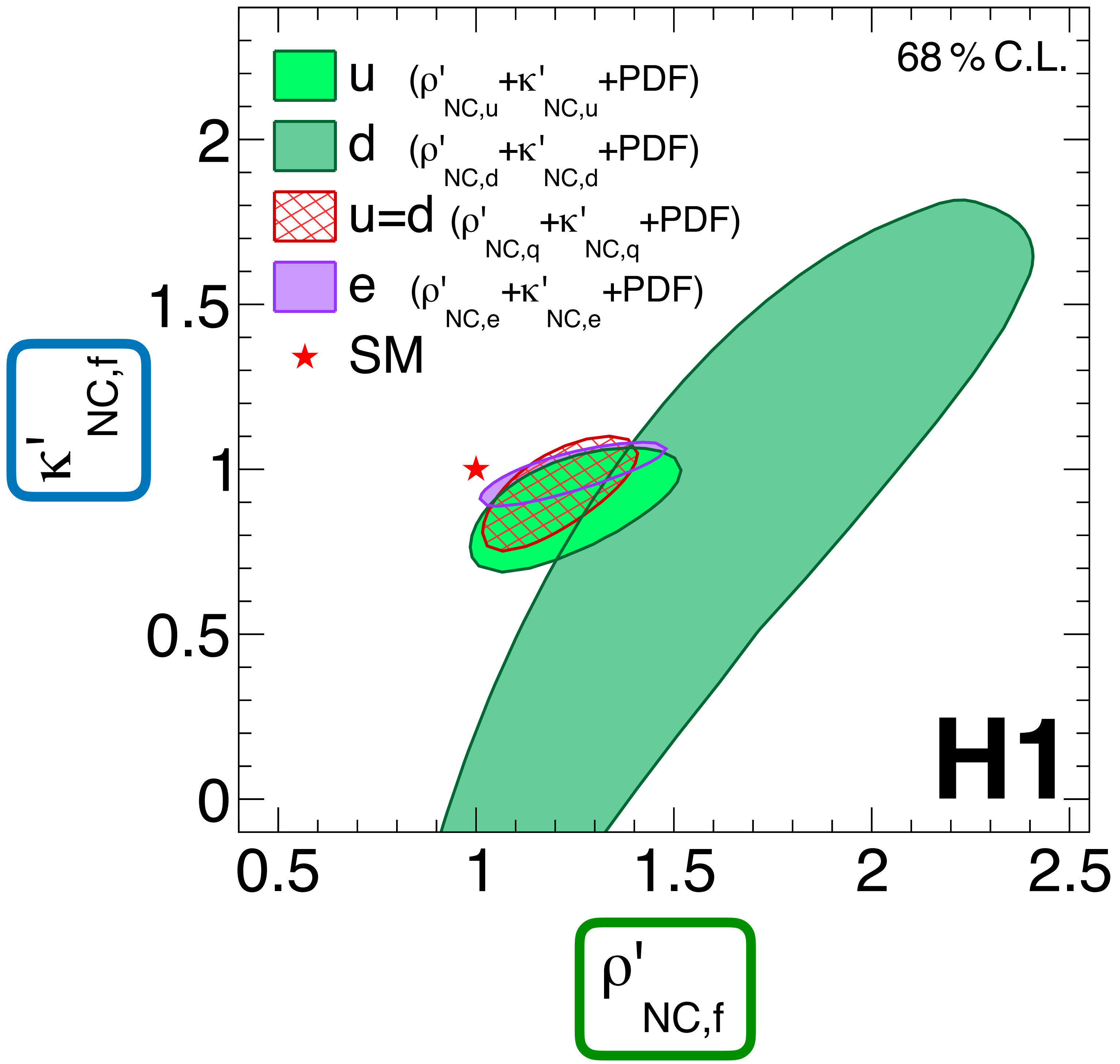


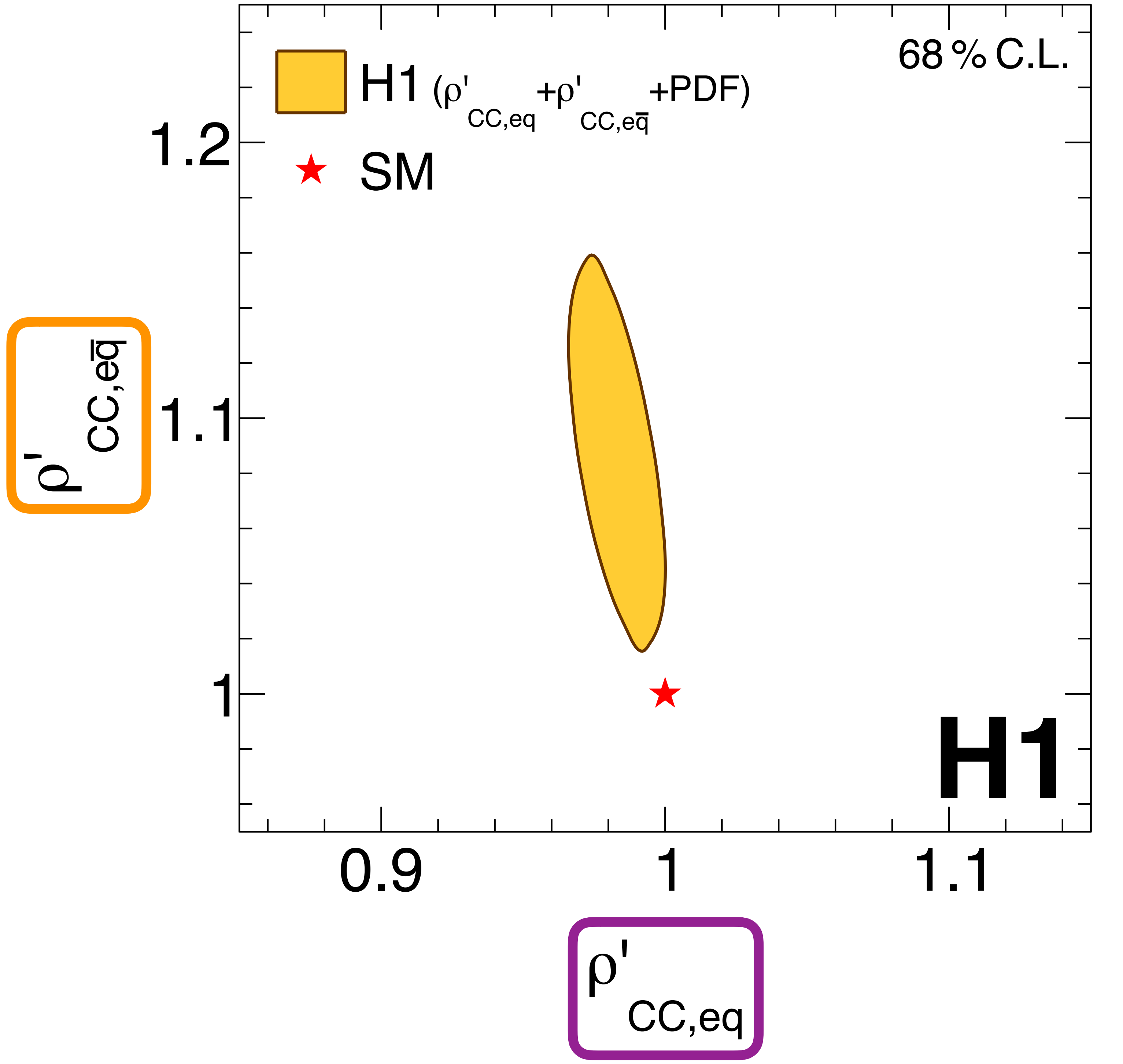
$$W_2^- = x\left(\boxed{\rho'^2_{CC,eq}}\rho^2_{CC,eq} U + \boxed{\rho'^2_{CC,e\bar{q}}}\rho^2_{CC,e\bar{q}}\overline{D}\right)$$

$$W_2^+ = x\left(\boxed{\rho'^2_{CC,eq}}\rho^2_{CC,eq} \overline{U} + \boxed{\rho'^2_{CC,e\bar{q}}}\rho^2_{CC,e\bar{q}} D\right)$$

$$xW_3^- = x\left(\boxed{\rho'^2_{CC,eq}}\rho^2_{CC,eq} U - \boxed{\rho'^2_{CC,e\bar{q}}}\rho^2_{CC,e\bar{q}}\overline{D}\right)$$

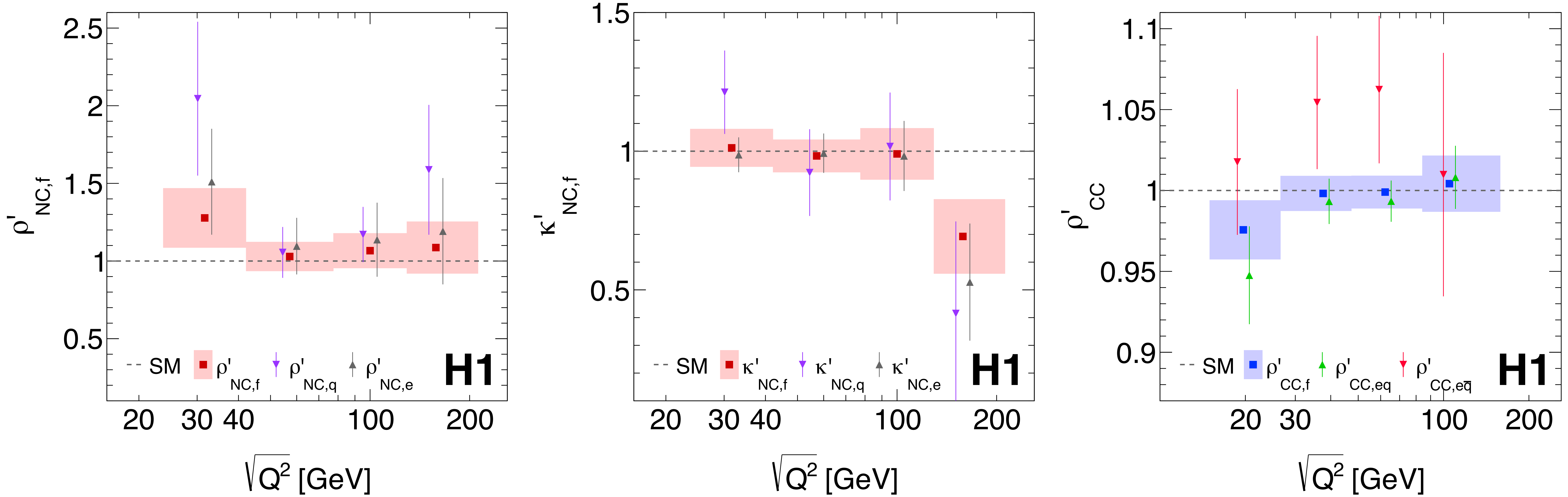
$$xW_3^+ = x\left(\boxed{\rho'^2_{CC,e\bar{q}}}\rho^2_{CC,e\bar{q}} D - \boxed{\rho'^2_{CC,eq}}\rho^2_{CC,eq}\overline{U}\right)$$





Scale dependance of ρ'_{NC}, κ'_{NC} and ρ'_{CC}

For the first time the scale dependence of ρ'_{NC}, κ'_{NC} and ρ'_{CC} has been studied:



No significant deviation from the SM expectation is observed

Eur.Phys.J.C78 (2018), 777

Summary

➤ Experiments at HERA have a rich history of BSM searches.

➤ Standard Model provides a good description of the HERA data, though some interesting effects are seen and studied.

➤ Wide kinematic range of the HERA data provides an unique opportunity to perform the simultaneous BSM and PDF analyses.