Testing the Standard Model at the intensity frontier

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plus discussions with G. De Lellis

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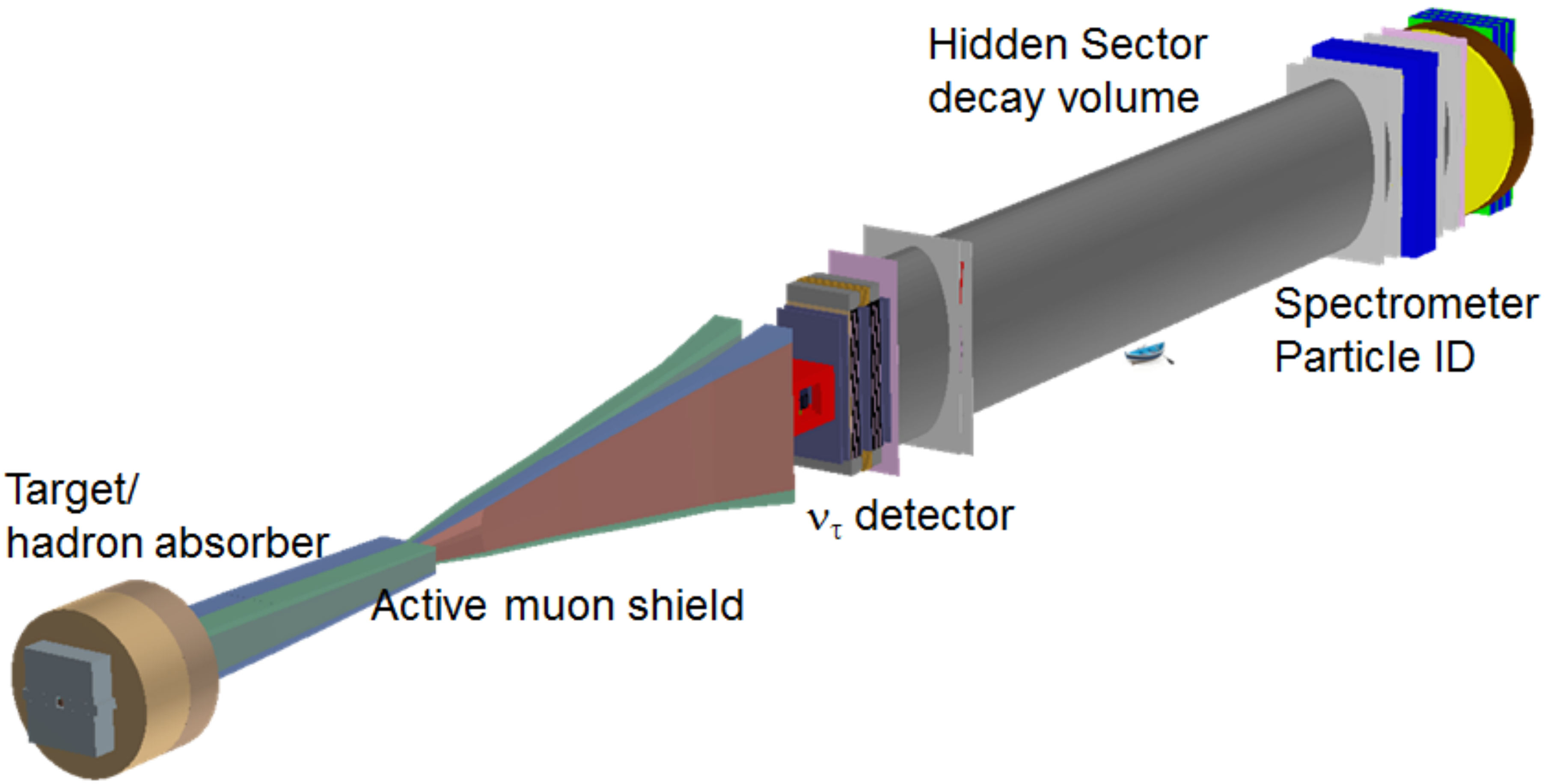
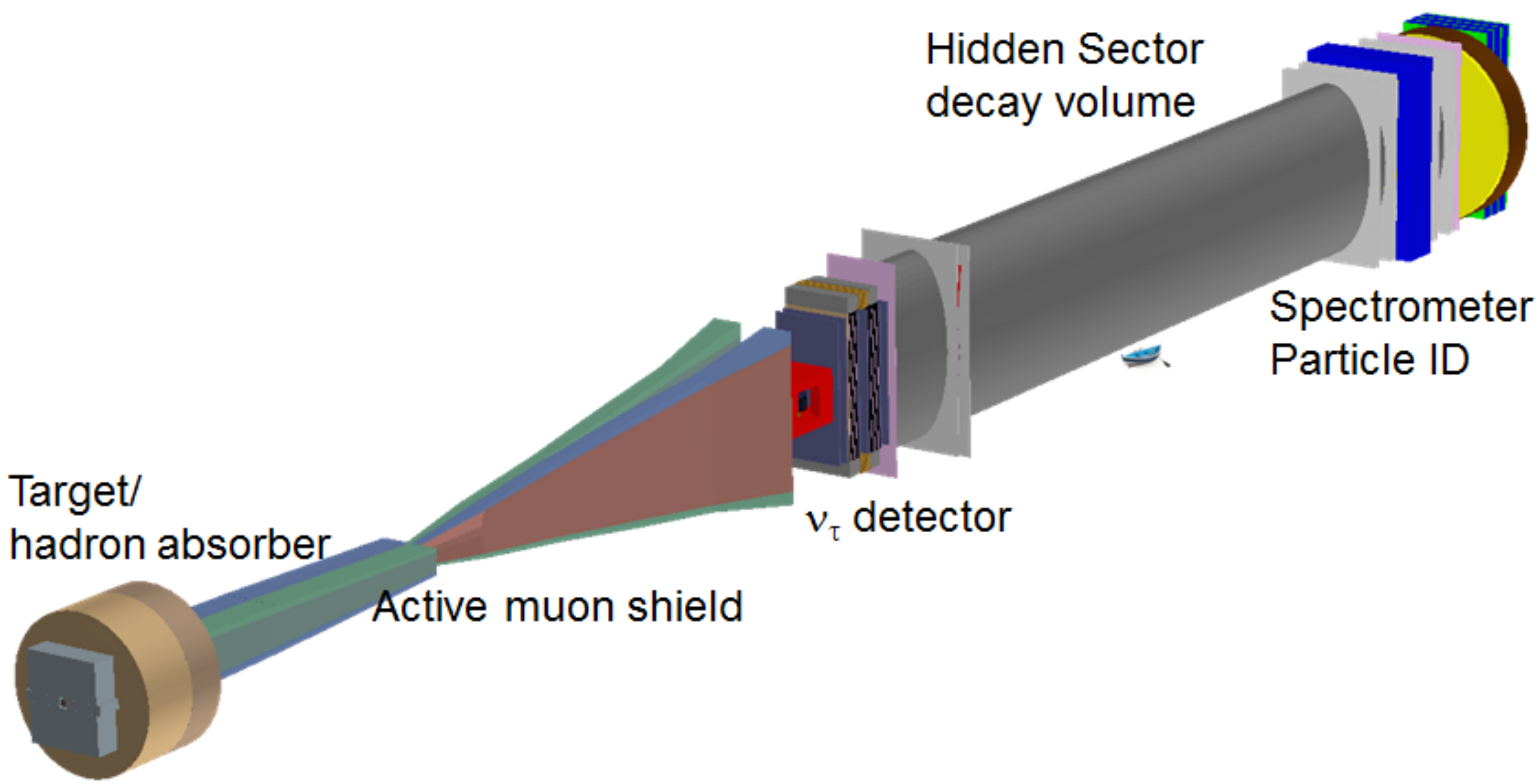
Search for Hidden Particles (SHiP)



- $2 \cdot 10^{20}$ protons on target will produce a flux of $\sim 10^{18}$ neutrinos and antineutrinos of the three known kind (standard)
- a neutrino detector could reveal light dark matter (see Pospelov's talk at this Institute)

Search for Hidden Particles (SHiP)



- Modern neutrino detector techniques means (sub) micro-metric precision capabilities and topological identification of tau leptons and charmed resonances for example

✓ tau neutrino cross sections

✓ bounds on tau neutrino magnetic moment

✓ nucleon strangeness

✓ exotic baryons

✓ trident production

not covered:

- high energy CC ν_e nucleus DIS cross section (never measured so far)
- elastic neutrino electron cross section (maj/dirac distinction)
  [S. P. Rosen (1982), Rodejohann, X. Xu, C.E. Yaguna (2017)]
- intrinsic nucleon charm determination
- …

tau neutrino and antineutrino

tau neutrino and antineutrino are the less known elementary particles in the Standard Model

- DONUT experiment at the Tevatron has seen 9 events with 1.5 background events

  ➡ No distinction among tau+ and tau-

  ➡ Total CC cross sections per nucleon (averaged) written as

$$\sigma_{\nu_\tau}^{\text{const}} = 0.72 \pm 0.24 \pm 0.36 \times 10^{-38} \quad \text{cm}^2\,\text{GeV}^{-1}$$

to be compared with the averaged muon neutrino cross section

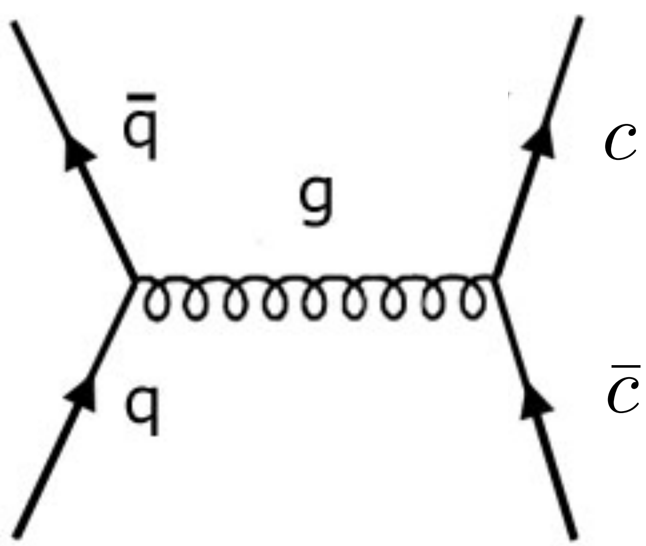
$$\sigma_{\nu_\ell} = 0.51 \times 10^{-38}\ \text{cm}^2$$

- Opera experiment has seen 5 events

  ➡ only tau-

Higgs boson at LHC13	
	$\sigma(pp \to H) = 48pb$
	$Br(H \to \gamma\gamma) = 2 \cdot 10^{-3}$
Integrated Luminosity (ATLAS+CMS)	$= 70(fb)^{-1}$
Acceptance and efficiency	$= 30\%$
~2000 Higgs bosons decaying to photons observed!	

$$\sigma^{cc}(pN@400GeV) \sim 18\mu b \ \times \ Br(c \to D_s) \sim 8\% \ \times \ Br(Ds \to \tau\nu_\tau) \sim 5\%$$



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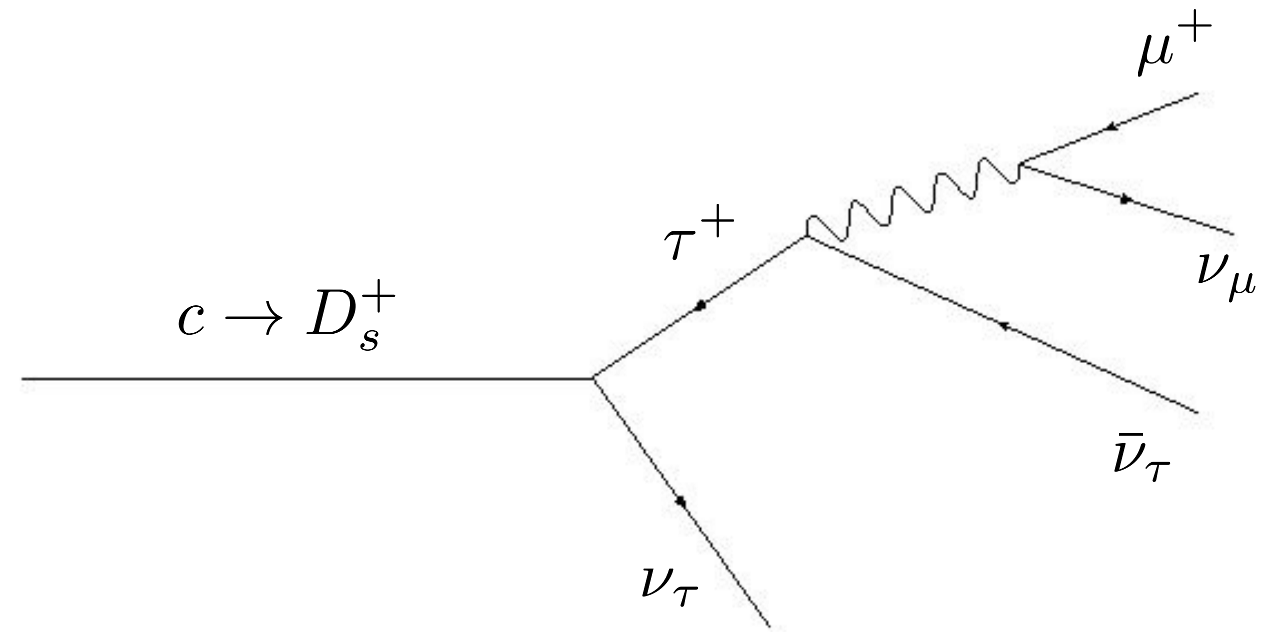


- tau neutrino and antineutrino production in proton a beam dump

Heavy quark production

- In general for bottom and charm production in hadronic collisions one finds large radiative corrections, and thus one expects large unknown higher order terms
- Non perturbative effects (suppressed by powers of Λ/m_Q) play a role (no theory for them)
- Still, understanding to what extent we can trust the theoretical machinery (factorization theorem) is extremely important
- We have to try models and compare with data:

Intrinsic Transverse Momentum

- Assuming that incoming partons have

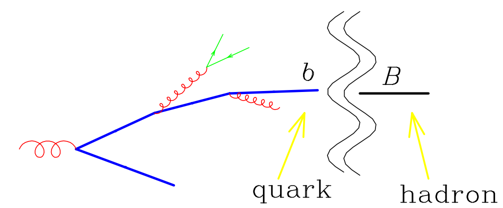
$$\langle k_T \rangle \sim \Lambda$$

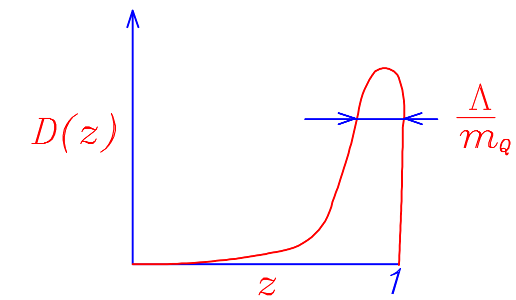
- perturbation theory generates

$$k_T \sim \alpha_S \cdot hard\ scale$$

- Affect transverse momentum of heavy quark pair, its azimuthal correlation and single transverse momentum distribution

Fragmentation





width of the distribution is $\approx \alpha_S \log p_T/m_Q$

- simple model a la Peterson not justified in hadron collisions

Monte Carlo models of hadronization

- Much more effects, for example:
  - Color Drag, from projectile remnants
  - leading particle enhancement
  - asymmetries

NLO + Parton Shower (and hadronisation)

- NLO provides important phenomenological features
- PS resums leading logarithmic enhancement and paired with hadronization models provide full event simulation
- Double counting of radiative corrections solved with implementation of the MC@NLO and POWHEG methods
- POWHEG master formula:

$$\bar{B}(\mathbf{\Phi}_n) = B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) + \left[\int d\Phi_{\rm rad}\left[R(\mathbf{\Phi}_{n+1}) - C(\mathbf{\Phi}_{n+1})\right] + \int \frac{dz}{z}\left[G_\oplus(\mathbf{\Phi}_{n,\oplus}) + G_\ominus(\mathbf{\Phi}_{n,\ominus})\right]\right]^{\bar{\mathbf{\Phi}}_n = \mathbf{\Phi}_n},$$

$$\Delta\left(\mathbf{\Phi}_n, p_{\rm T}\right) = \exp\left\{-\int \frac{\left[d\Phi_{\rm rad}\, R(\mathbf{\Phi}_{n+1})\,\theta(k_{\rm T}\left(\mathbf{\Phi}_{n+1}\right) - p_{\rm T})\right]^{\bar{\mathbf{\Phi}}_n = \mathbf{\Phi}_n}}{B(\mathbf{\Phi}_n)}\right\}$$

$$d\sigma = \bar{B}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{\Delta\left(\mathbf{\Phi}_n, p_{\rm T}^{\rm min}\right) + \Delta\left(\mathbf{\Phi}_n, k_{\rm T}\left(\mathbf{\Phi}_{n+1}\right)\right)\frac{R\left(\mathbf{\Phi}_{n+1}\right)}{B(\mathbf{\Phi}_n)} d\Phi_{\rm rad}\right\}_{\bar{\mathbf{\Phi}}_n = \mathbf{\Phi}_n}$$

- In the following we will show results obtained with: POWHEG hvq + PYTHIA-6.4.27
- Uncertainties from matching and hadronization could be studied comparing with MC@NLO and linking PYTHIA and HERWIG respectively
- The hvq process with POWHEG can be downloaded from: www.powhegbox.mib.infn.it

Distributions

- proton on target collisions data at energies 250GeV are available
- several πN experimental results

➡ pion pdf fitted using DY muon pair production

- NA10 with pions at 196GeV and 286GeV (155k events)
- E615 with pions at 252GeV (35k events)

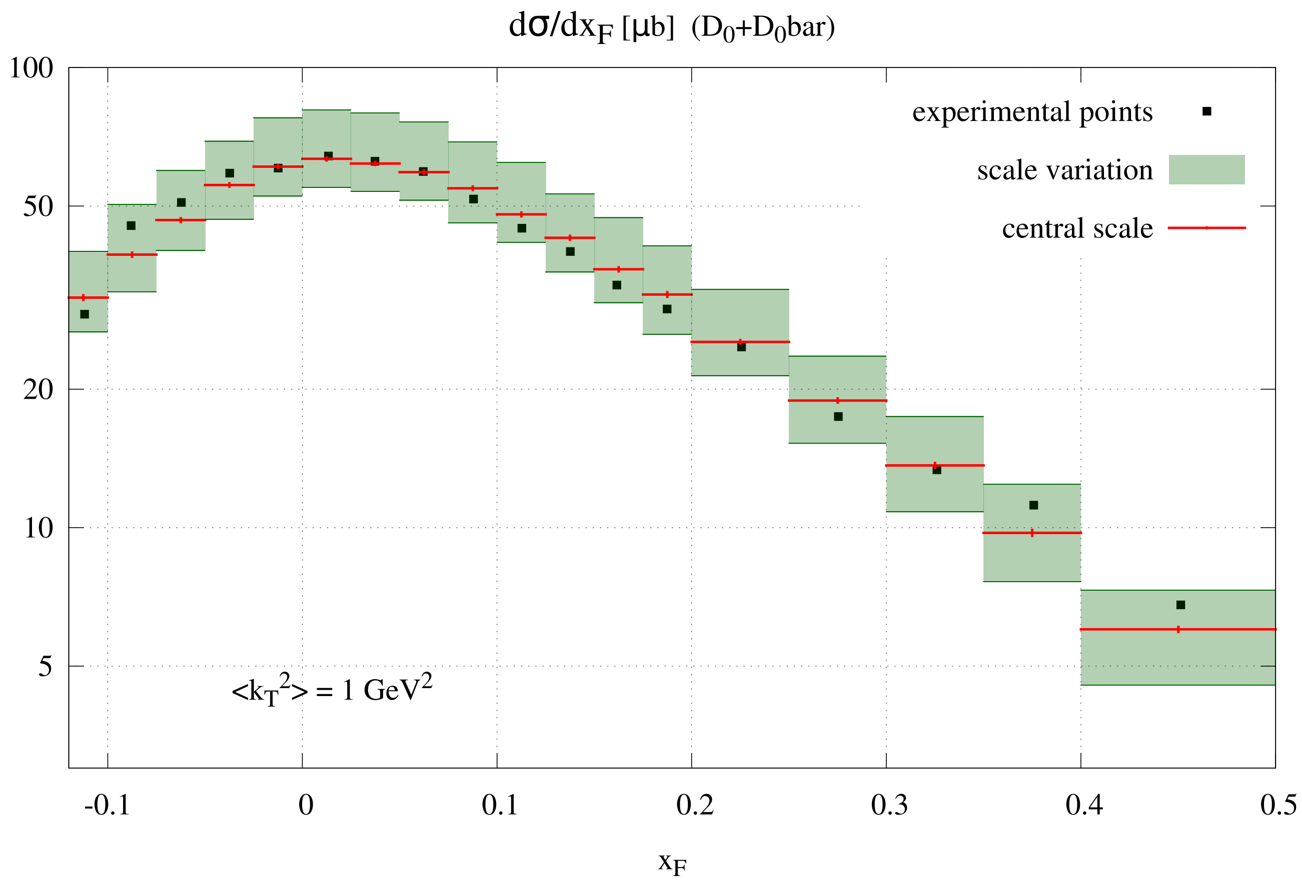
➡ No data available to fit pion pdf at $x \lesssim 0.2$

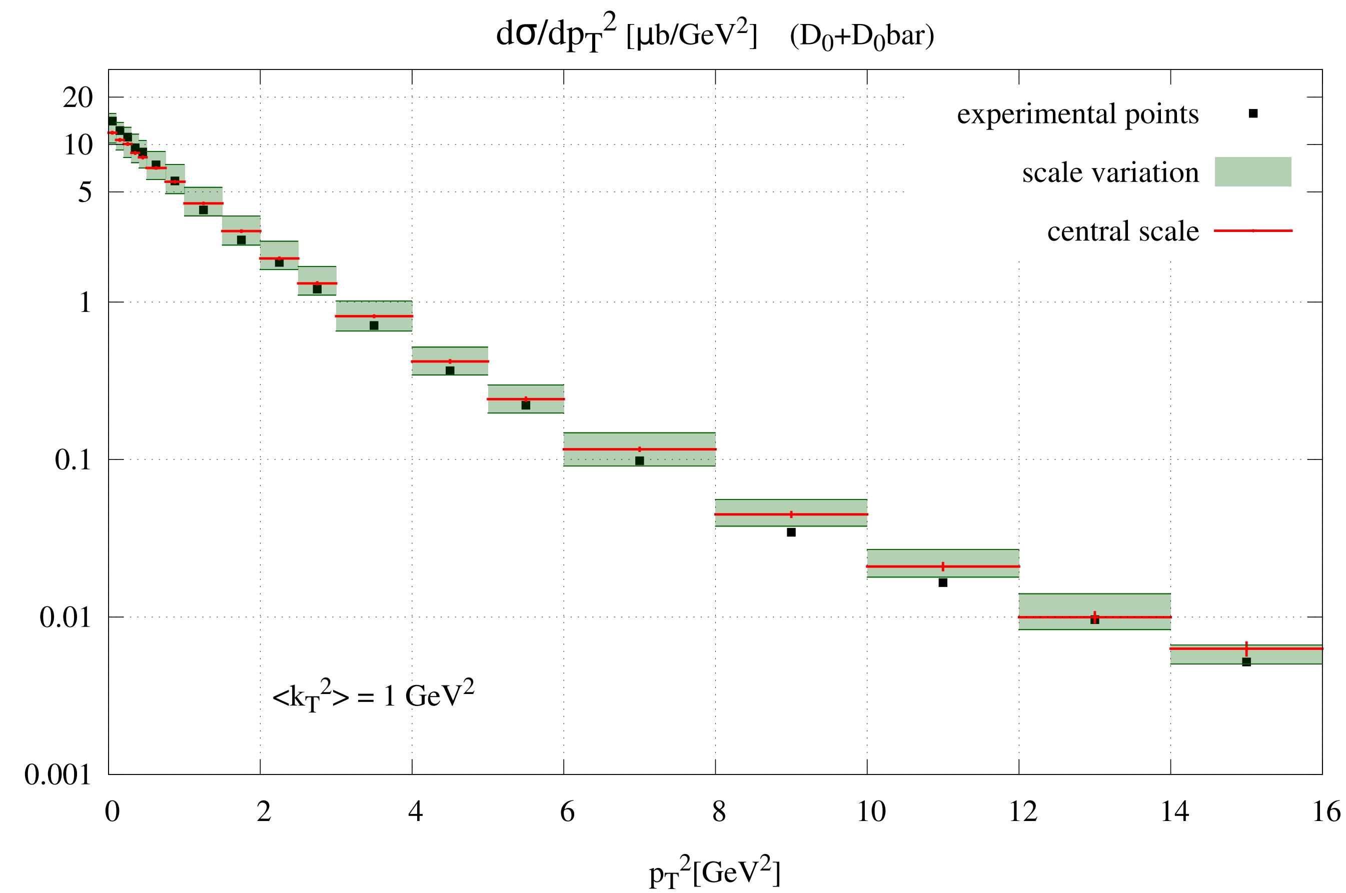
➡ several sets available that differ for the assumptions on the sea, even using them to estimate pdf uncertainty this could be underestimated

E791: results $D_0 + \bar{D}_0 \; (x_F > 0)$ x_F and p_T^2 distribution

500GeV π⁻ on target

Pion - single differential

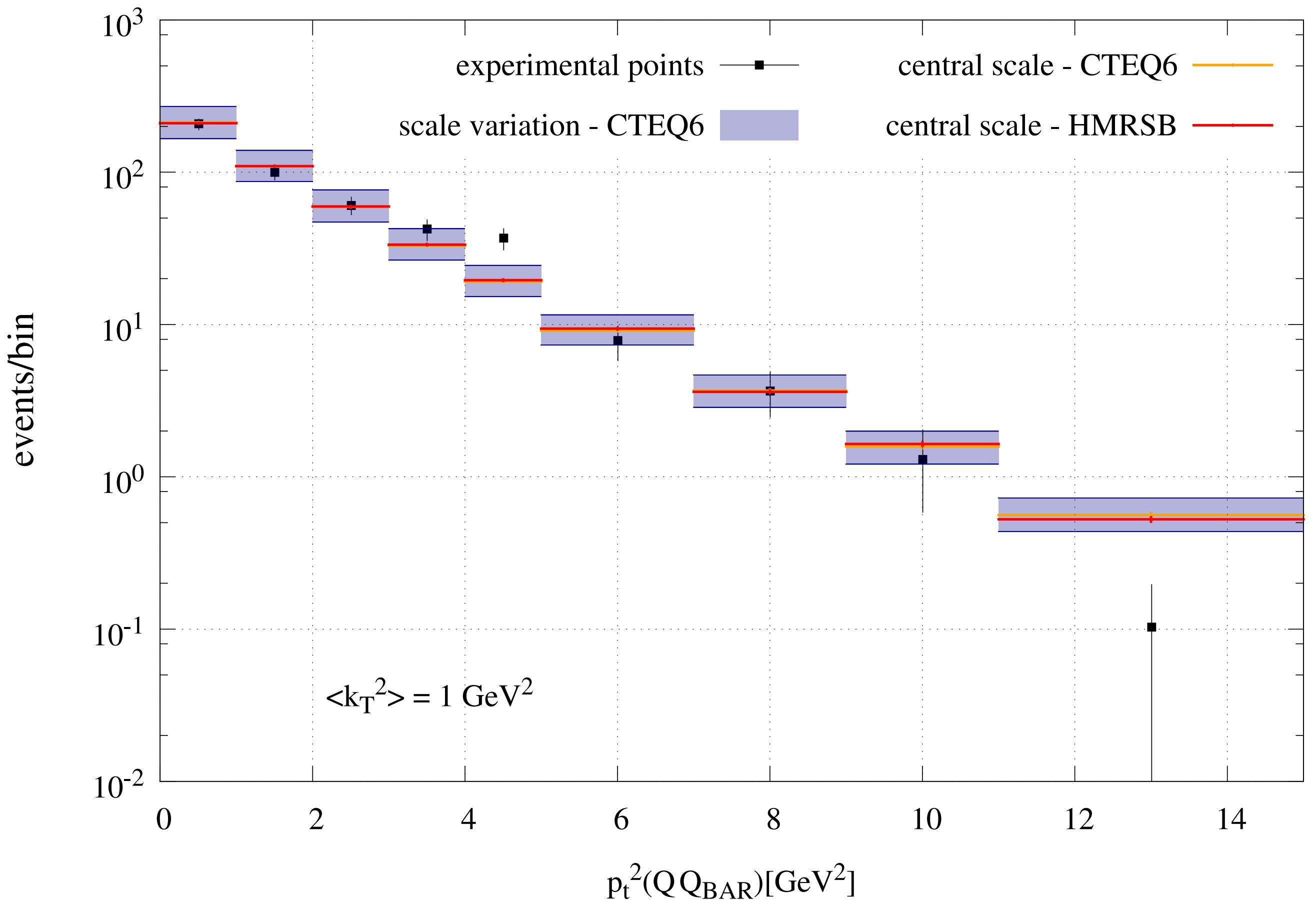


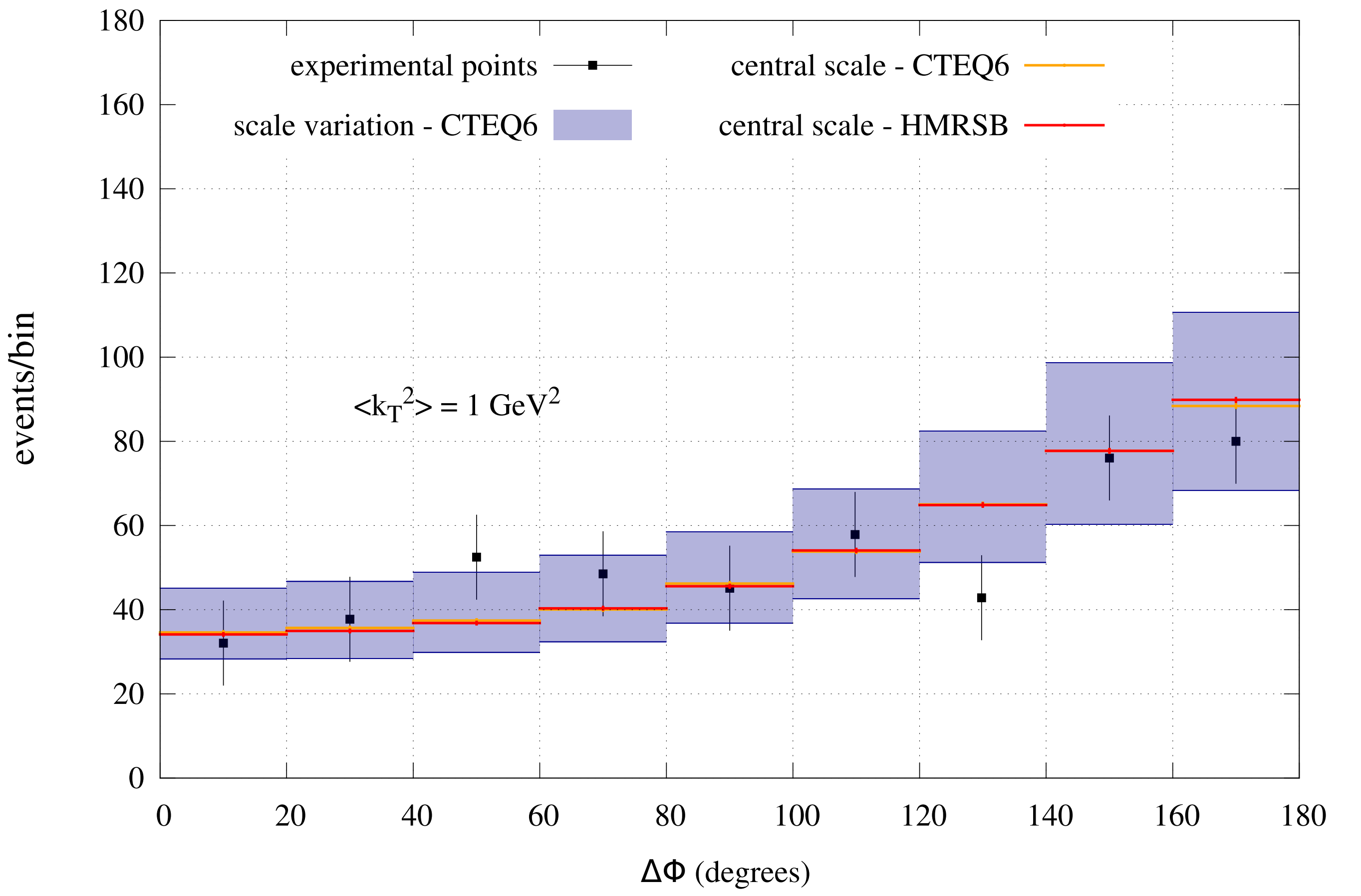


WA92: results for charm associate production

350GeV π^- on target

pion: double differential spectra

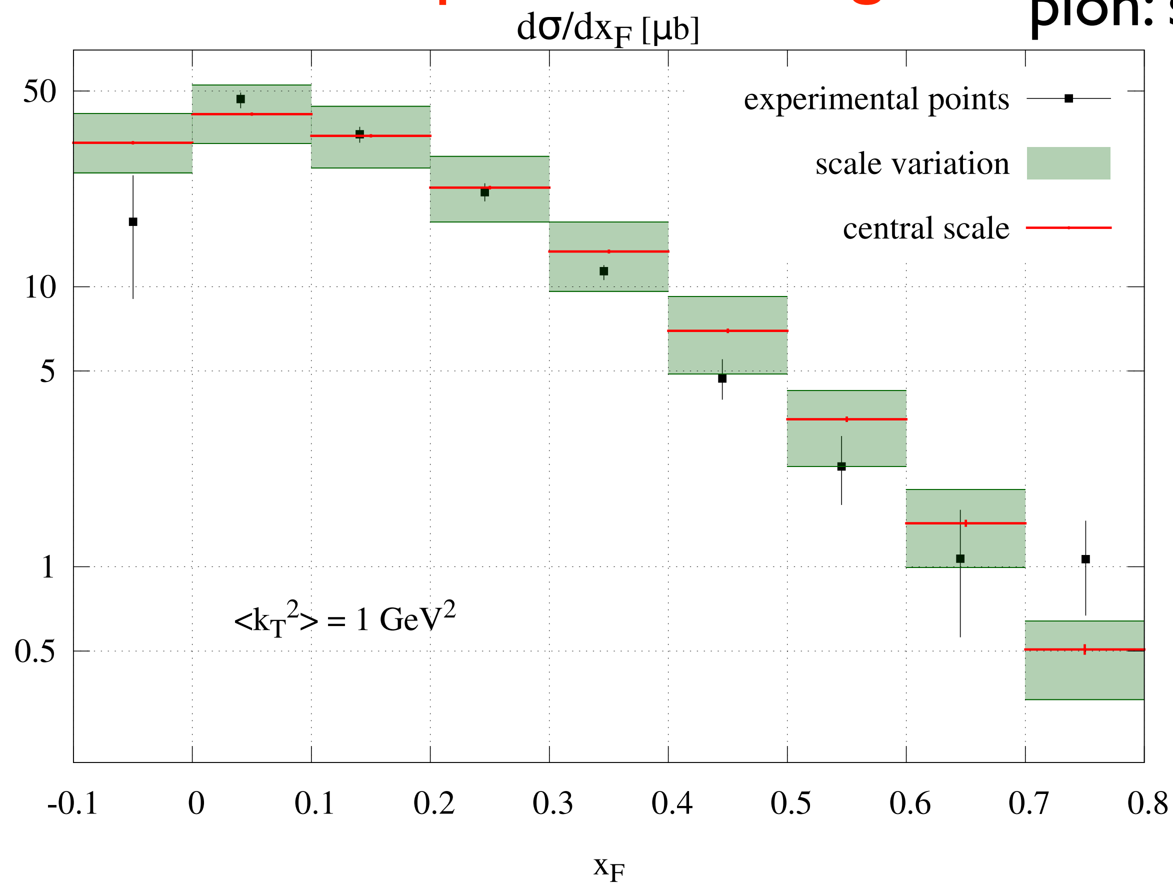


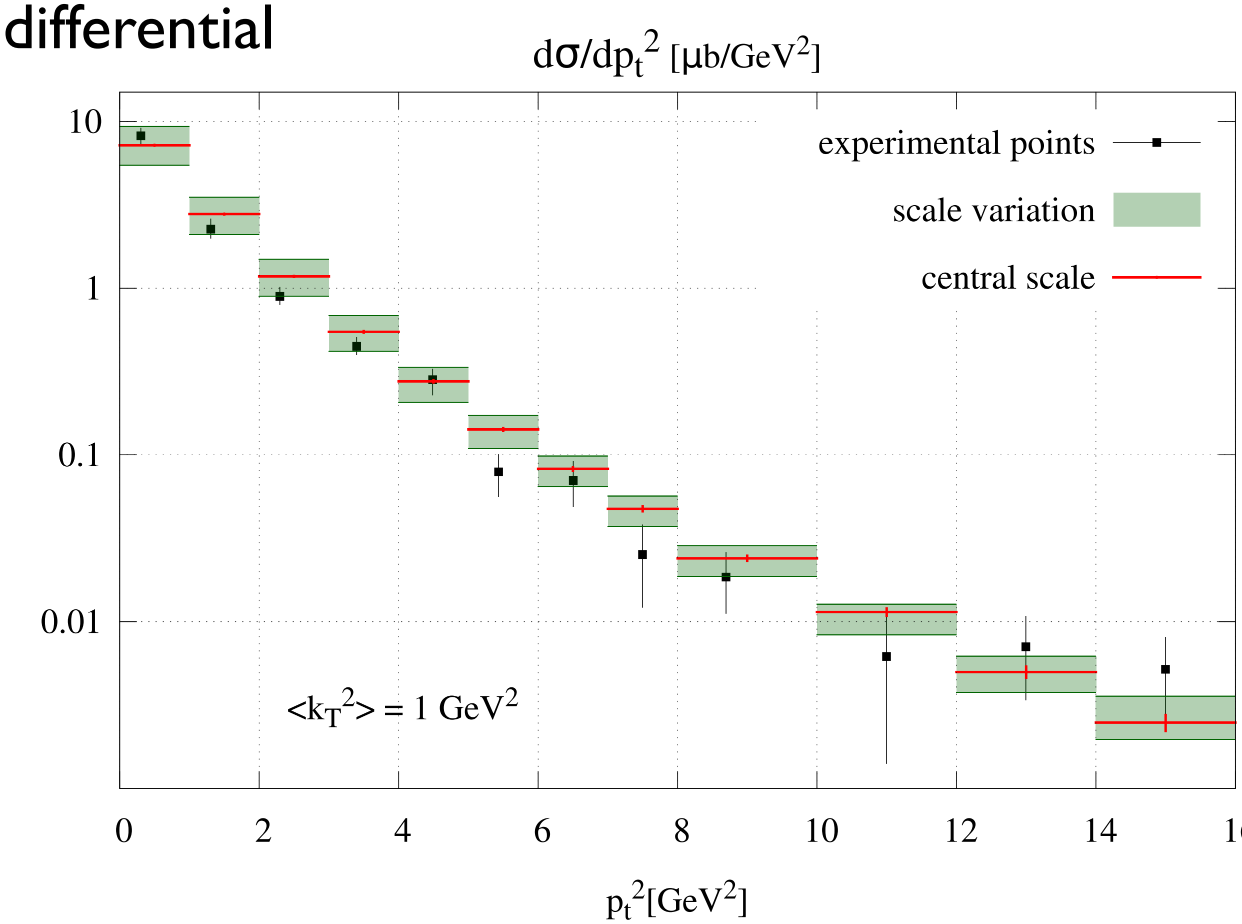


E769: results for all charmed mesons: x_F and p_T^2 distribution

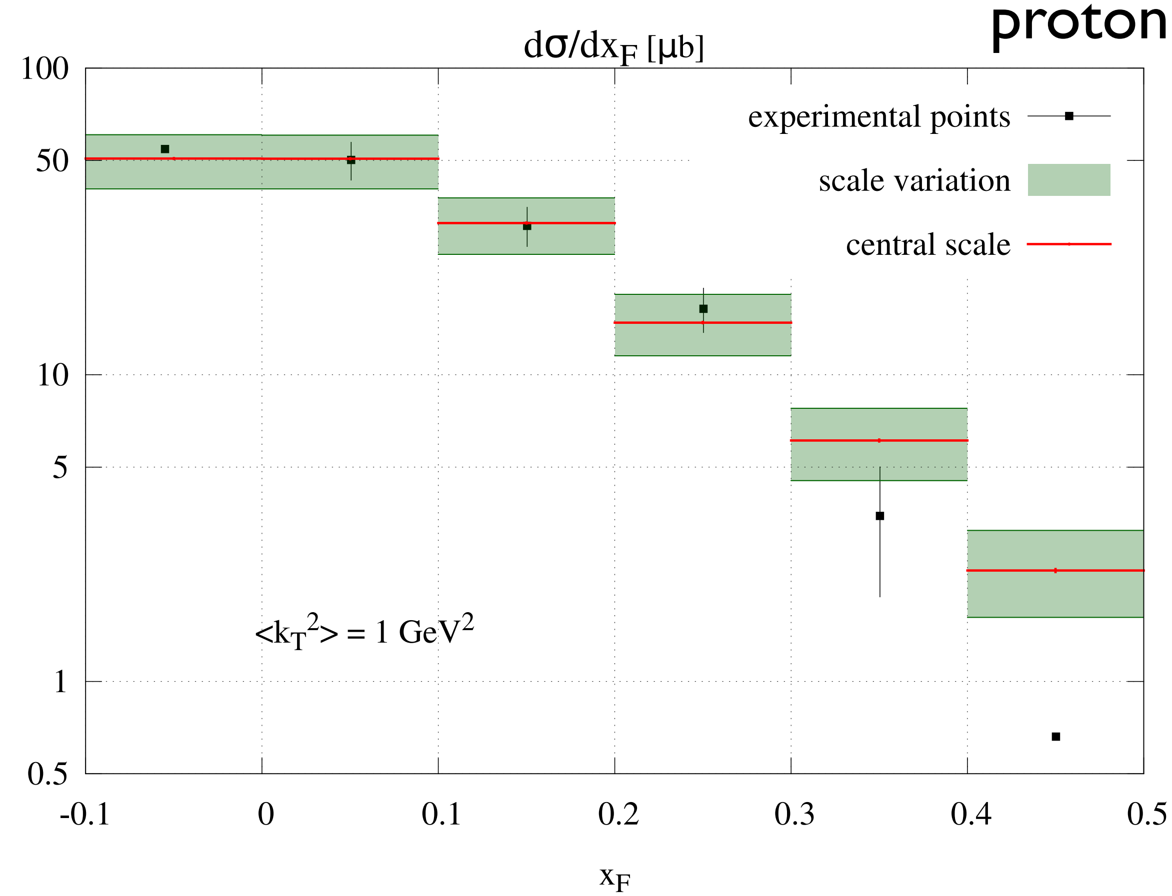
250GeV π^- and proton on target

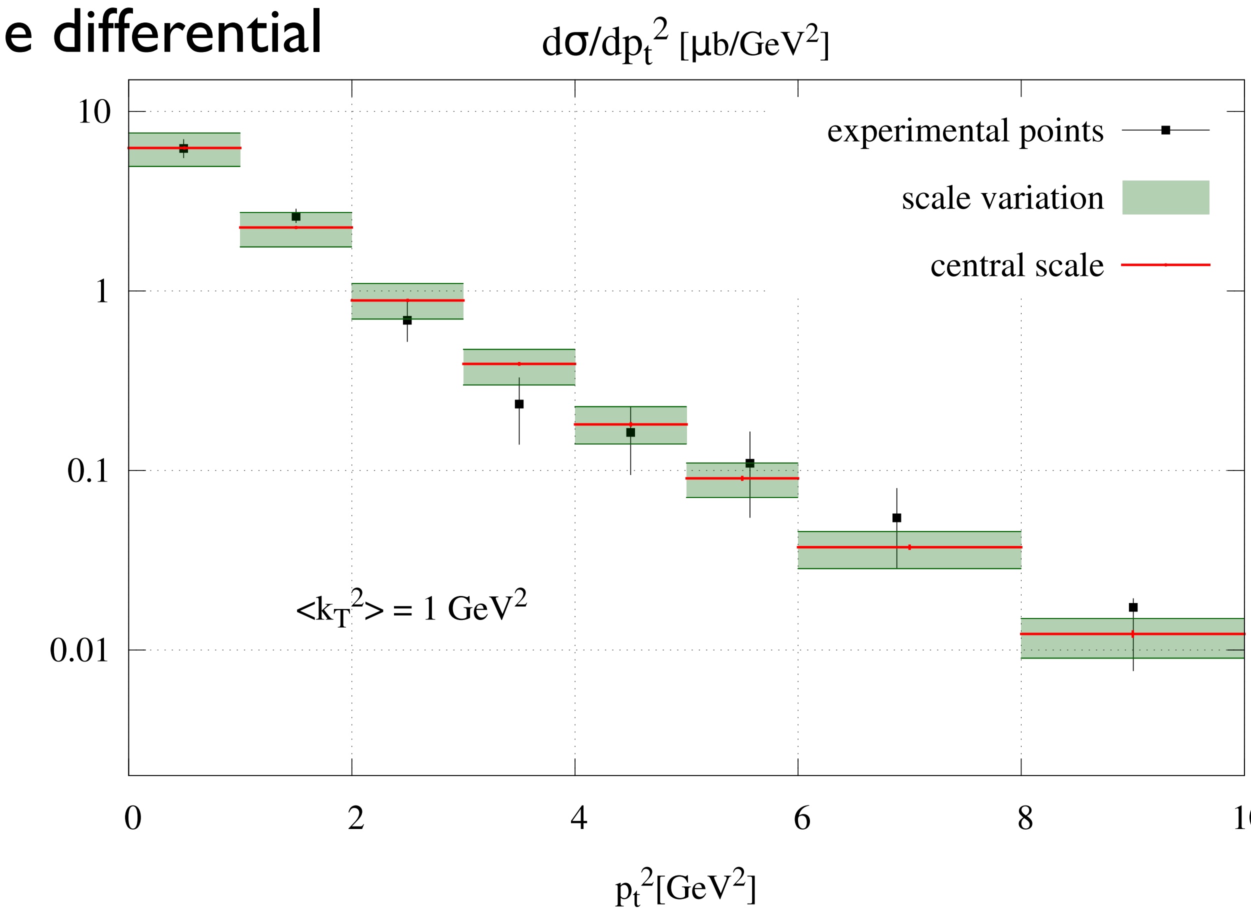
pion: single differential



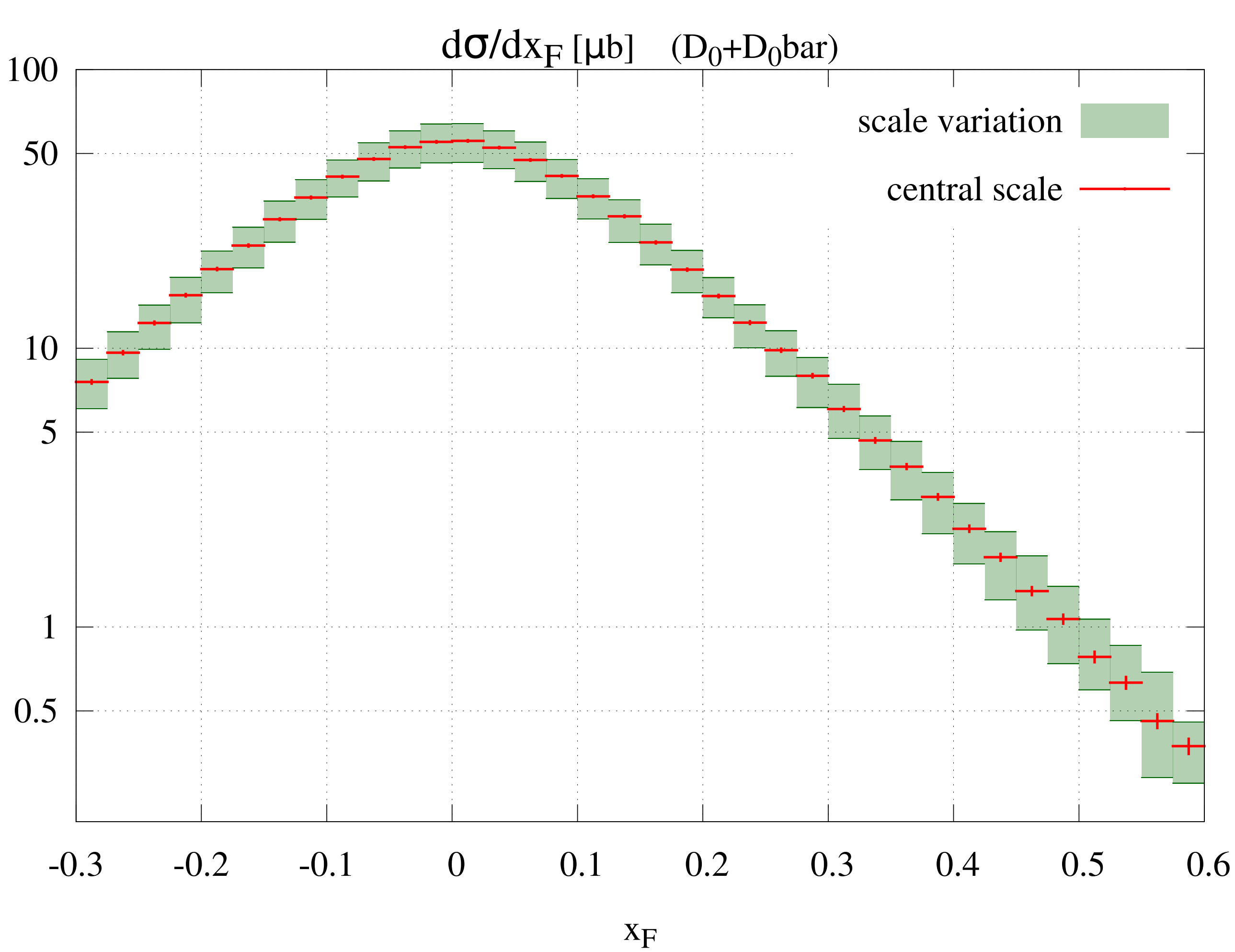


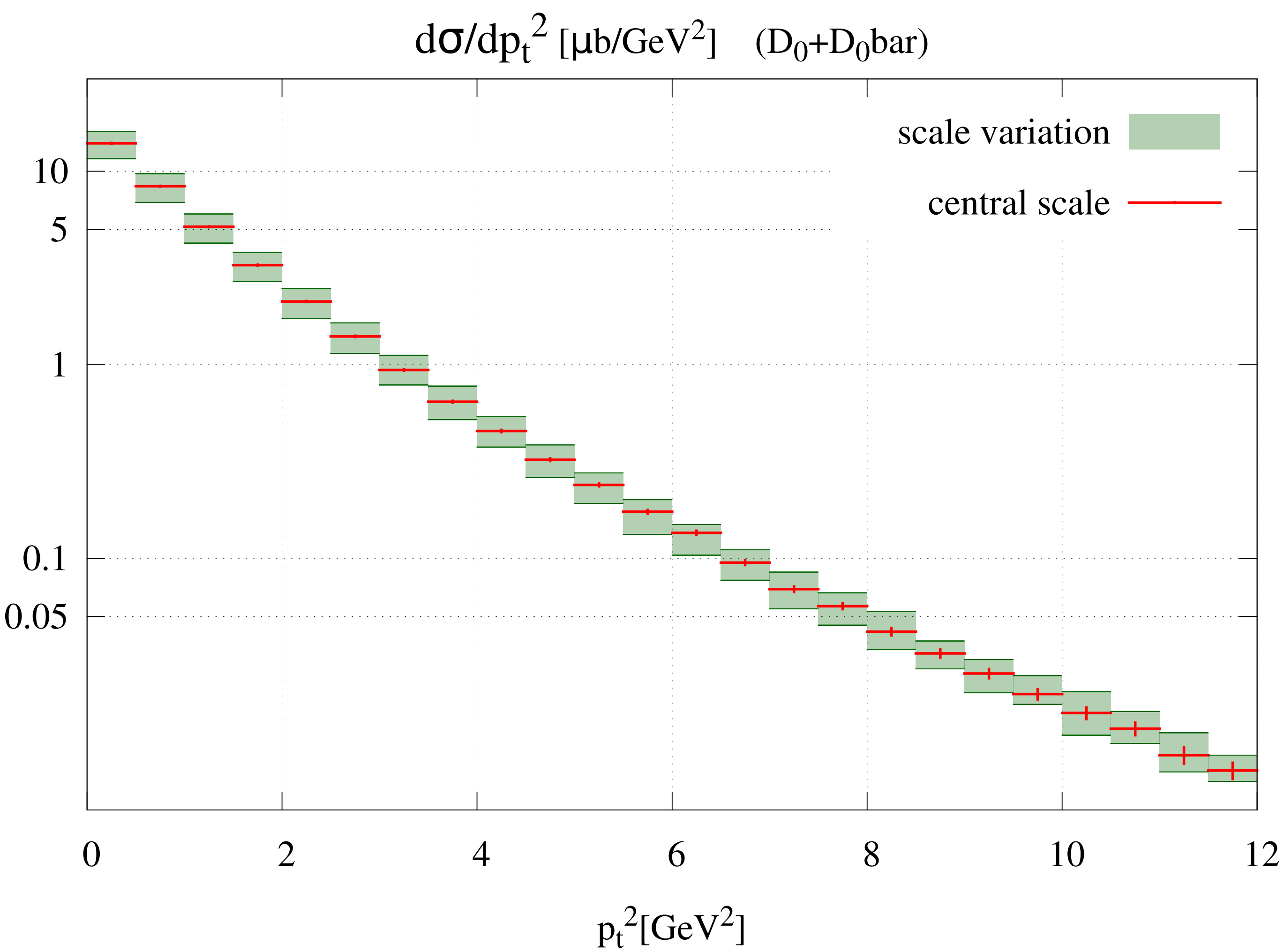
proton: single differential





charm production in a 400GeV proton beam dump (SHiP)

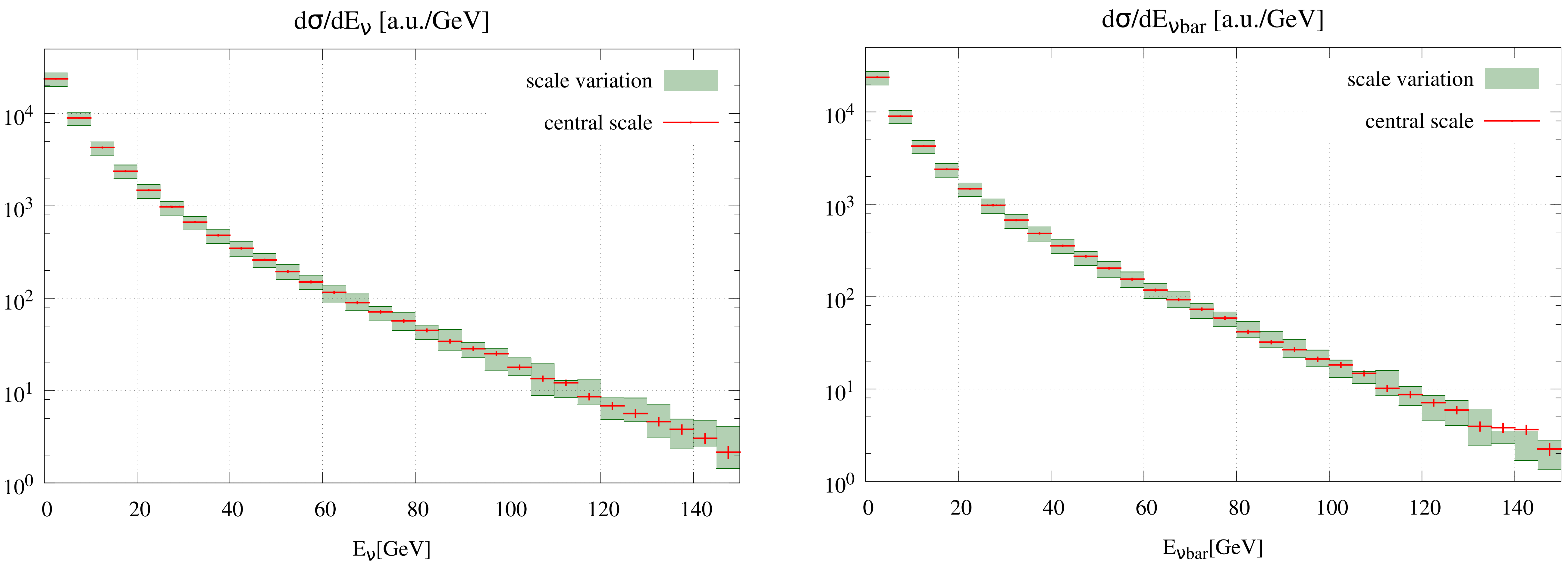




New measurement would be important for a number of reasons:

- cascade effects
- fix normalization
- fragmentation fractions
- solid base for simulation

tau neutrino spectra in SHiP



- 10^{16} tau neutrino and antineutrino produced in SHiP proton beam dump experiment

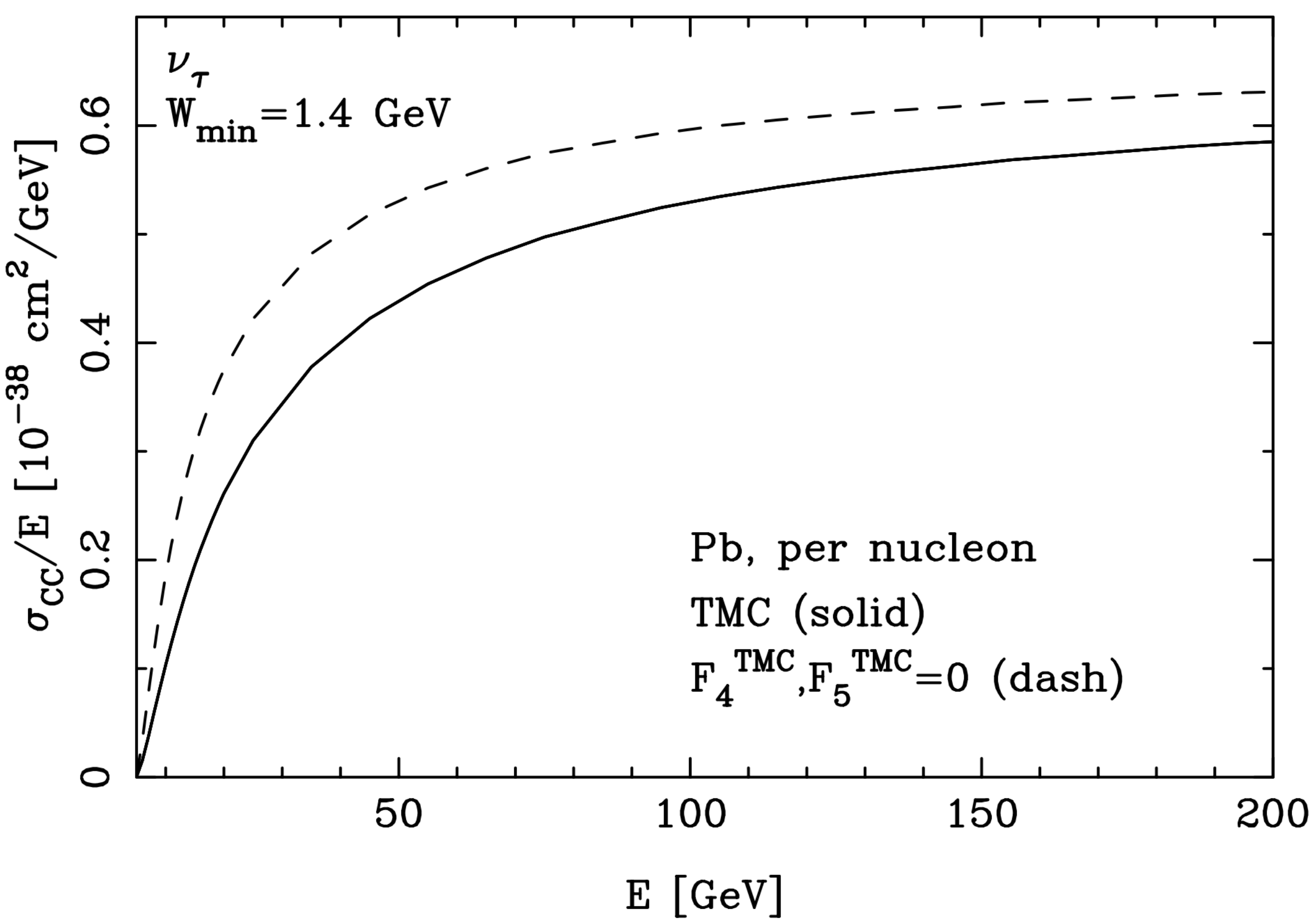
In the Standard Model tau neutrino charged current cross section is

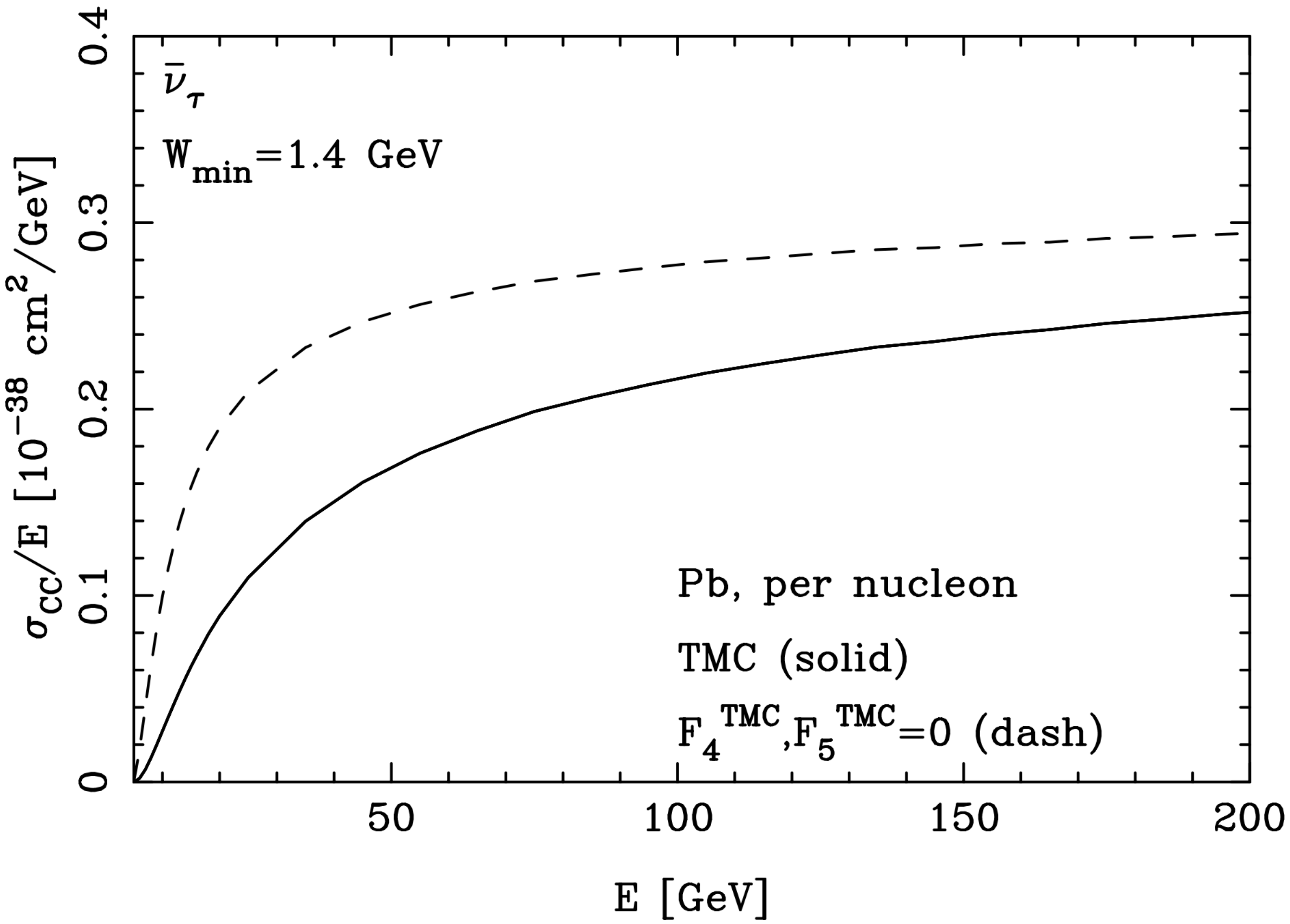
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx\ dy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2 x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})y\right] F_2$$
$$\pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right] F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x} F_4 - \frac{m_\tau^2}{E_\nu M} F_5 \Bigg)$$

- +F3 applies to neutrino scattering and −F3 to antineutrinos.
- first opportunity to measure the structure functions F4 and F5
- At the Born level, neglecting target mass corrections, the Albright-Jarlskog relations apply:

$$F_4 = 0$$
$$F_5 = \frac{F_2}{2x}$$

tau neutrino cross sections receive large contributions from F5

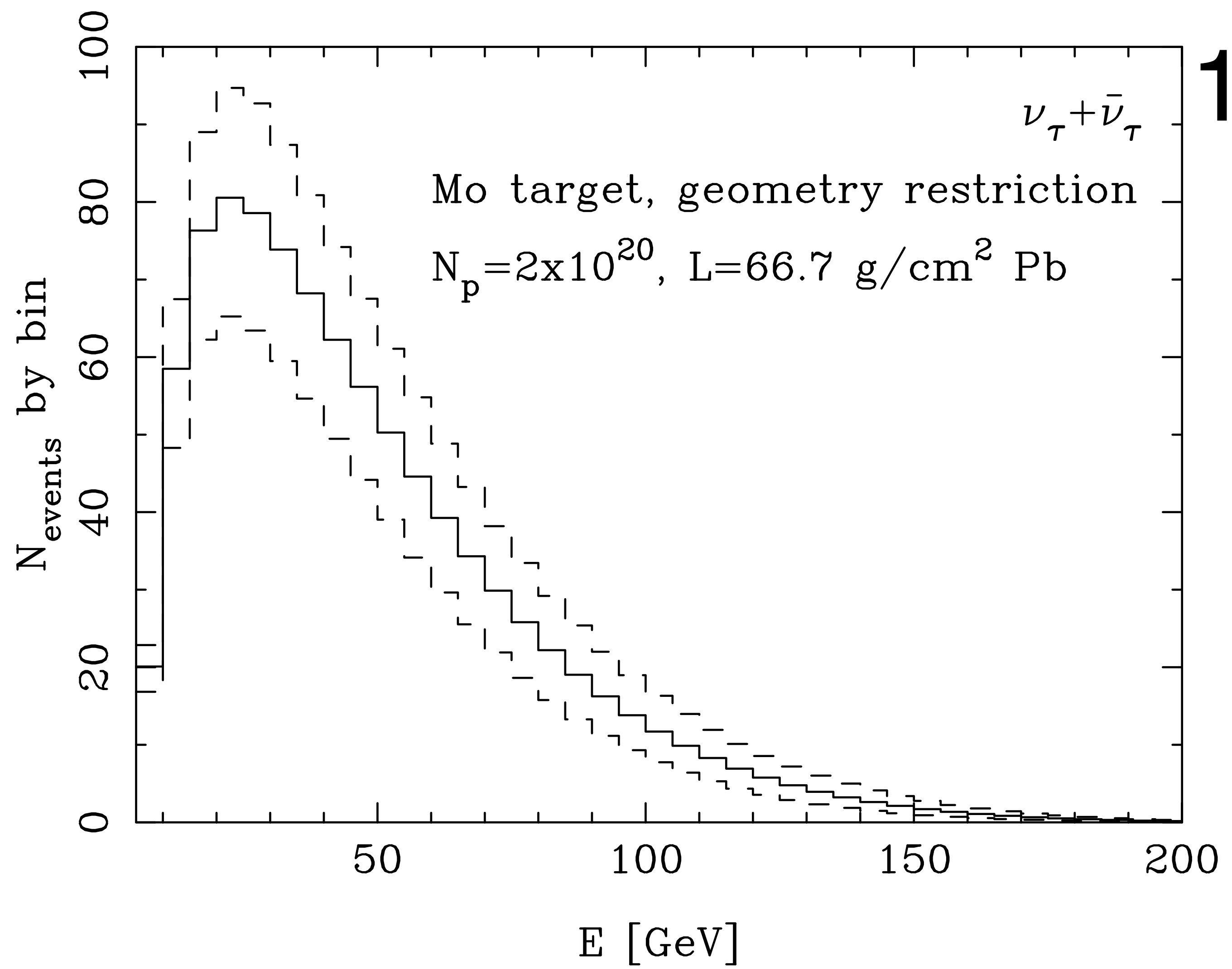




[Kretzer and M. H. Reno (2002)]

Number of tau neutrino and antineutrino events expected at SHiP

[SHiP Physics Paper: Alekhin et al (2015)]



1ton

- Thousands of charged current tau neutrino and anti-neutrino interactions expected in SHiP
  - ✓ ~7000 neutrino and 2500 antineutrino events in a 10ton target
  - ✓ assuming 30% detection efficiency means ~3000 fully reconstructed events
  - ✓ exact numbers depend on the distance and geometry of the detector

Will be possible to probe lepton (non-)universality with tau neutrino scattering

[Liu, Rashed, Datta 2016]

- assuming the existence of new scalar and tensor coupling

$$\mathcal{H}_{\text{eff}} = \frac{G_F V_{ud}}{\sqrt{2}} \left[\bar{u}(A_S + B_S \gamma_5) d \, \bar{l}(1-\gamma_5)\nu_l + T_L \, \bar{u}\sigma^{\mu\nu}(1-\gamma_5) d \, \bar{l}\sigma_{\mu\nu}(1-\gamma_5)\nu_l \right]$$

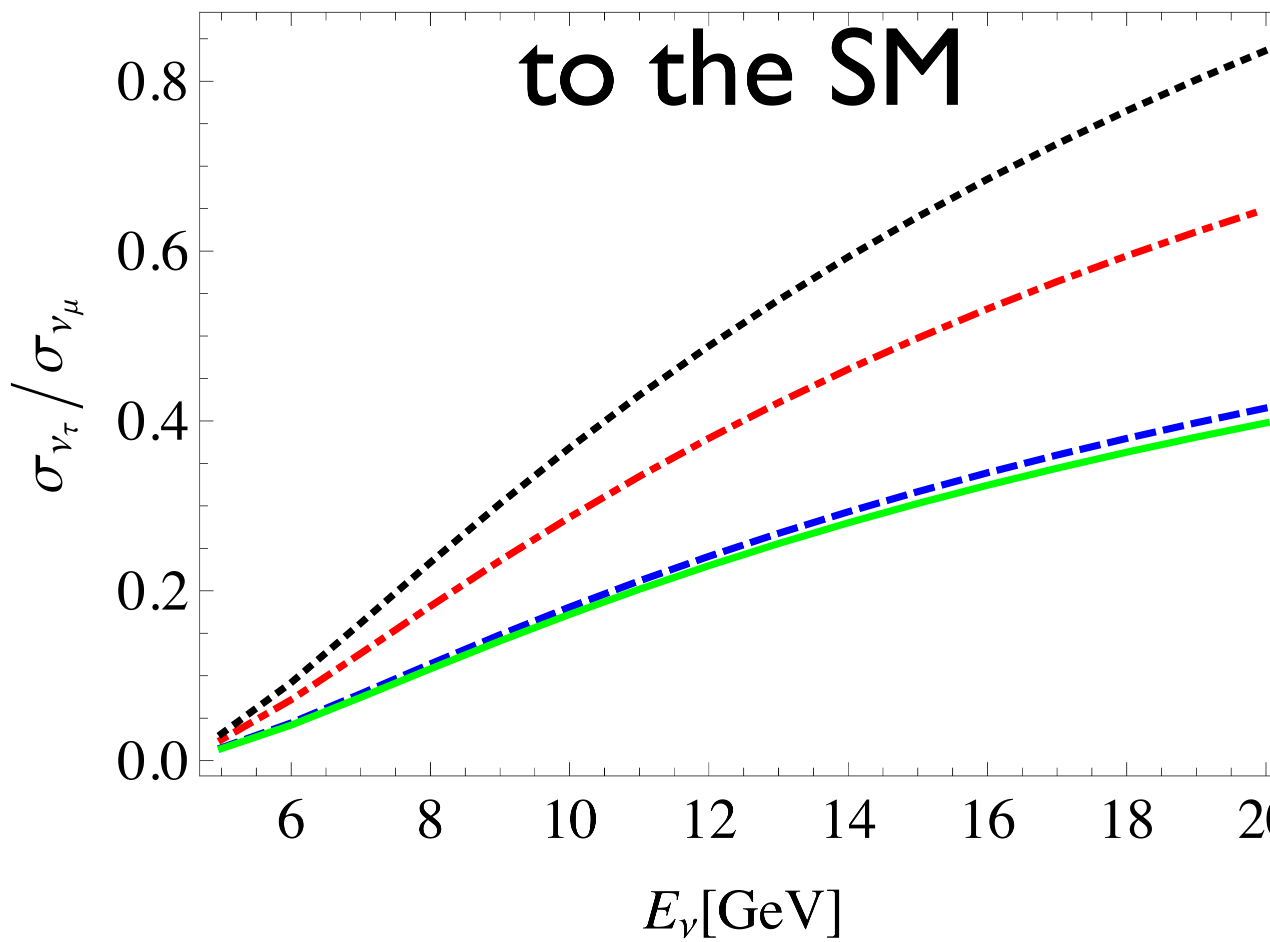
- the strongest constraints come from:

➡ $\tau^-(k_1) \to \nu_\tau(k_2) + \pi^-(q)$ (scalar)

➡ $\tau(p) \to \pi^-(p_1) + \pi^0(p_2) + \nu_\tau(p_3)$ (tensor)

➡ nevertheless, differences wrt the SM might still be quite large

Green line corresponds to the SM



tau neutrino magnetic moment

- neutrino-photon interaction in the SM is extremely small and proportional to neutrino mass

$$\mu_\nu = \frac{3\, e\, G_F\, m_\nu}{8\, \pi^2\, \sqrt{2}} \simeq (3.2 \times 10^{-19}) \left(\frac{m_\nu}{1\, \mathrm{eV}} \right) \mu_B$$

SM: $$\left.\frac{\sigma_{(\nu e, \bar{\nu} e)}}{dT}\right|_{SM} = \frac{G_F^2 m_e}{2\pi} \left[(g_V \pm g_A)^2 + (g_V \mp g_A)^2 \times \left(1 - \frac{T}{E_\nu}\right)^2 - (g_V^2 - g_A^2) \frac{m_e T}{E_\nu^2} \right]$$

NP: $$\left.\frac{\sigma_{(\nu e, \bar{\nu} e)}}{dT}\right|_{\mu_\nu} = \frac{\pi \alpha_{em}^2 \mu_\nu^2}{m_e^2} \left(\frac{1}{T} - \frac{1}{E_\nu} \right)$$

[Domogatsky and D. Nadezhin (1970)]

μ_ν	Actual limit (μ_B)
ν_e	$2{,}9 \cdot 10^{-11}$
ν_μ	$6{,}8 \cdot 10^{-10}$
ν_τ	$3.9 \cdot 10^{-7}$

DONUT experiment

- In SHiP with 2·10[20] POT and a target of 10 ton one would get

$$N_{ev} = 4.3 \times 10^{15} \frac{\mu_\nu^2}{\mu_B^2}$$

- Backgrounds are:

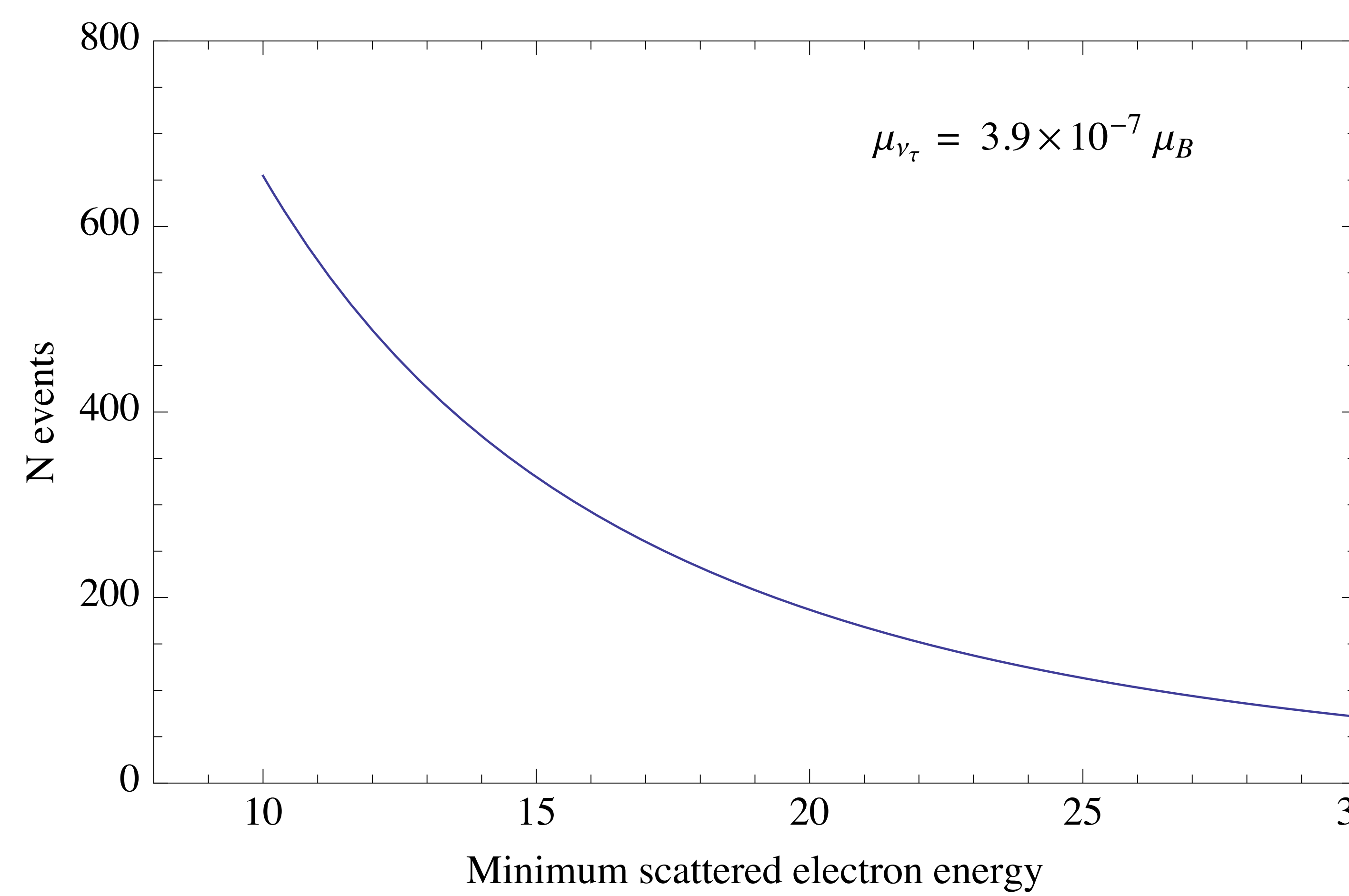
➡ Standard Model elastic scattering

➡ ν_e scattering off nuclei

Scattering angle limited in the laboratory frame

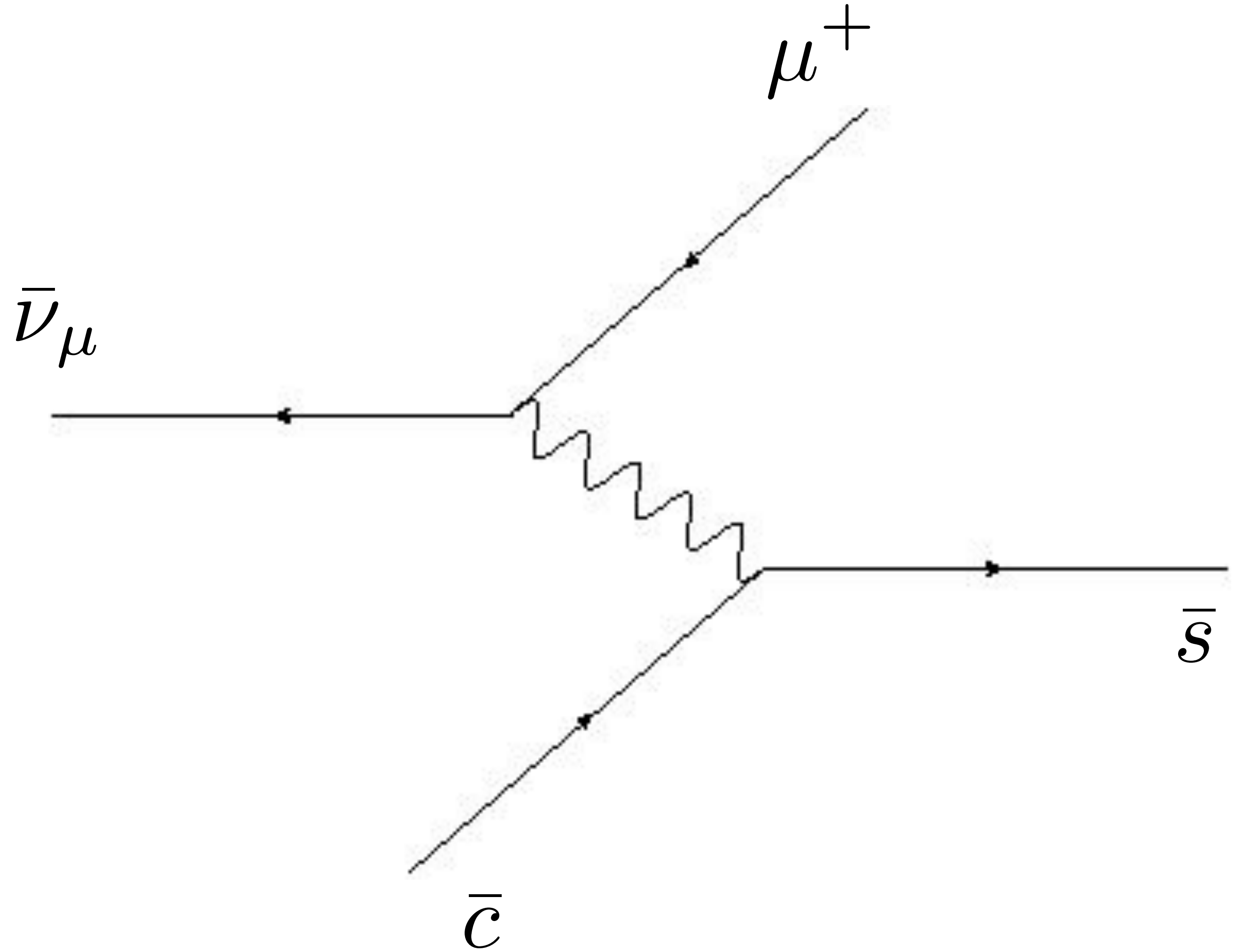
$$\theta^2_{\nu-e} < 2m_e/E_e$$

$E_e > 1GeV$ ➡ $\theta_{\nu-e} < 30$ mrad



Strangeness

Probing strangeness with neutrinos



Proton strangeness

- Precise knowledge of nucleon strangeness is critical for BSM searches at the LHC

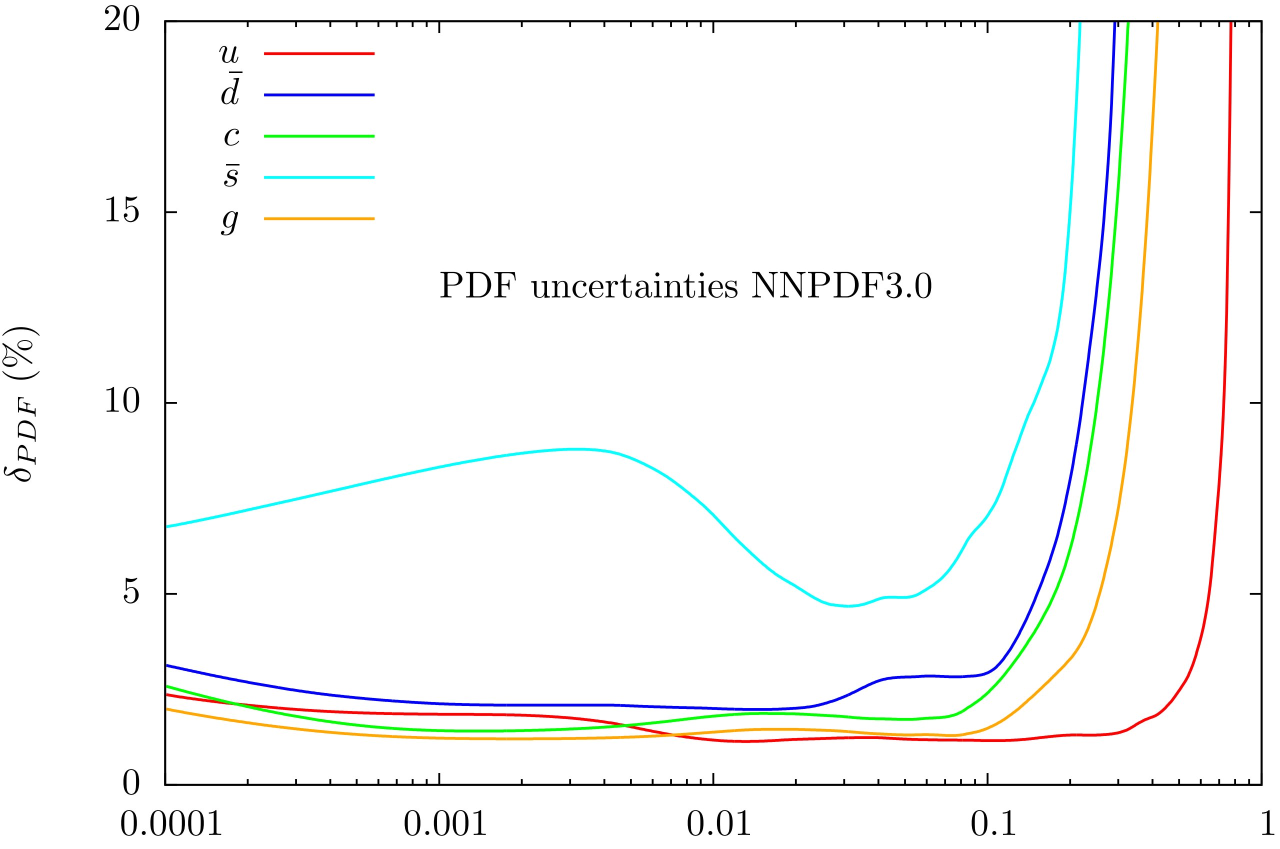
- and for important Electroweak theory tests

  - Example: W mass measurement
  - W production at 14TeV comes from ~ 80% ud + 20% cs

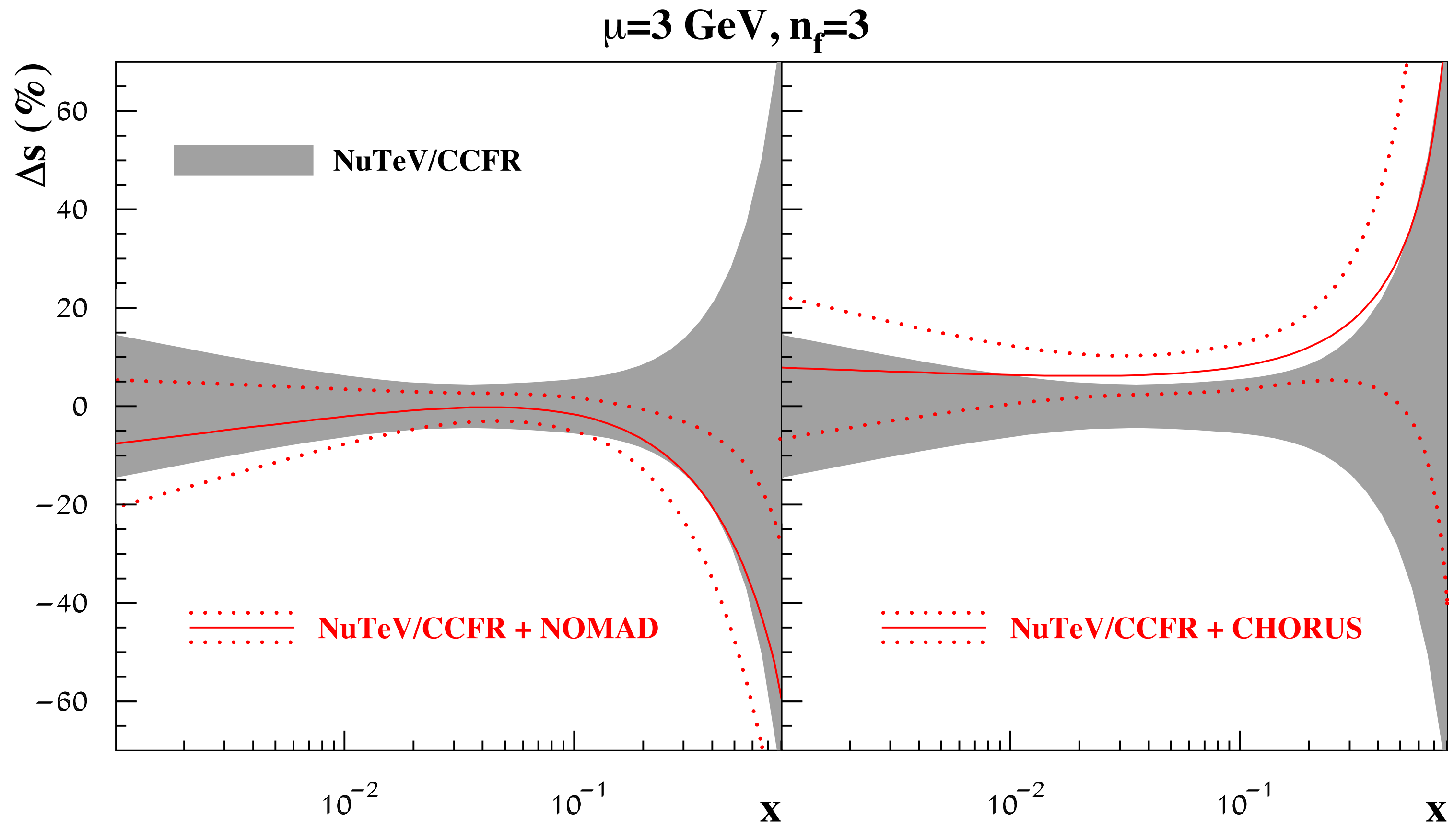
				Standard Model
M_W	[GeV]	Tevatron	80.387 ± 0.016	80.363 ± 0.006
		LEP	80.376 ± 0.033	

W mass measurement provides a fundamental test of the internal consistency of the Standard Model

PDF uncertainty relevant for W mass measurement



- PDF uncertainty of different flavors
- strangeness uncertainty ~3 times larger then the others



- ABM12 PDF
- strange see quark comes basically from NuTeV/CCFR

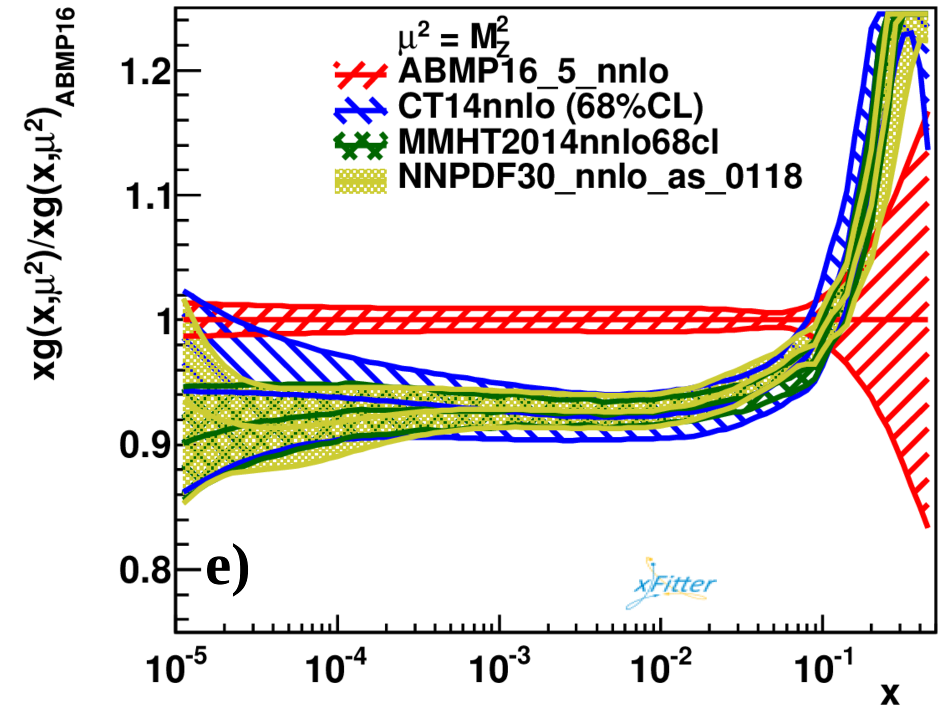
Comparison plots between PDF sets

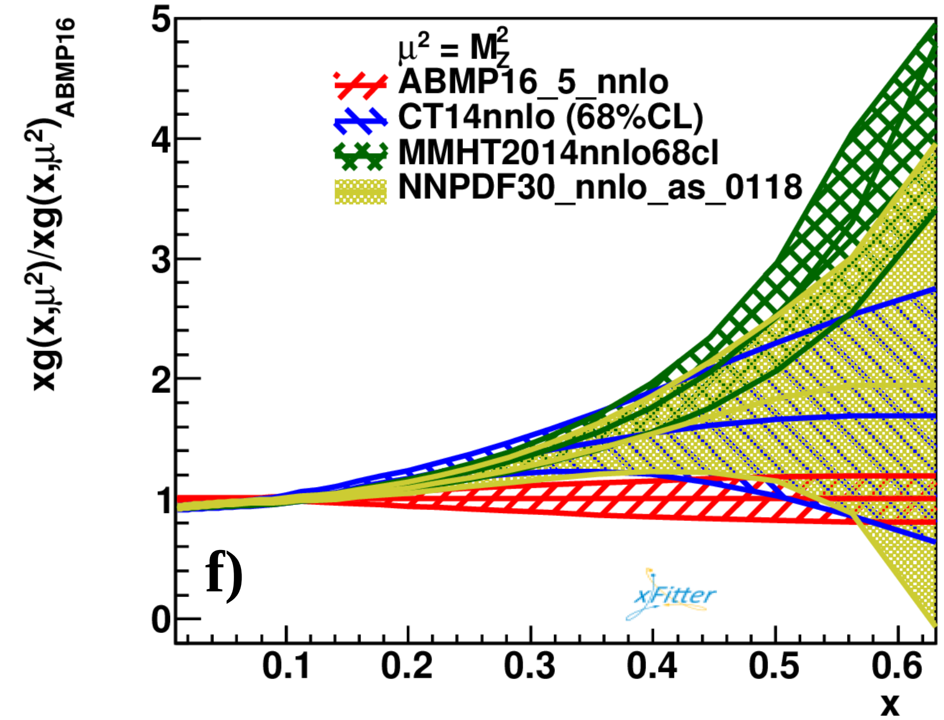
In general there is good consistency among different PDF determinations … with intriguing differences especially between

ABMP16
and
CT14/MMHT2014/NNPDF3.0

For example the gluon distribution over the all *x* range

or the up quark in the large-*x* region





[Plots from Alekhin et al, arXiv:1701.05838]

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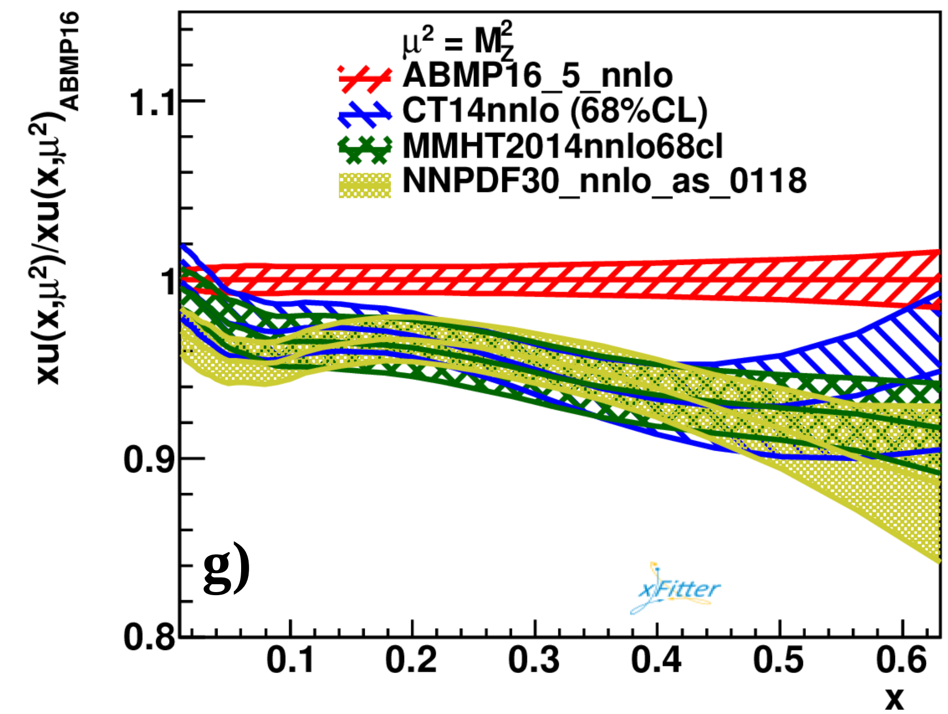

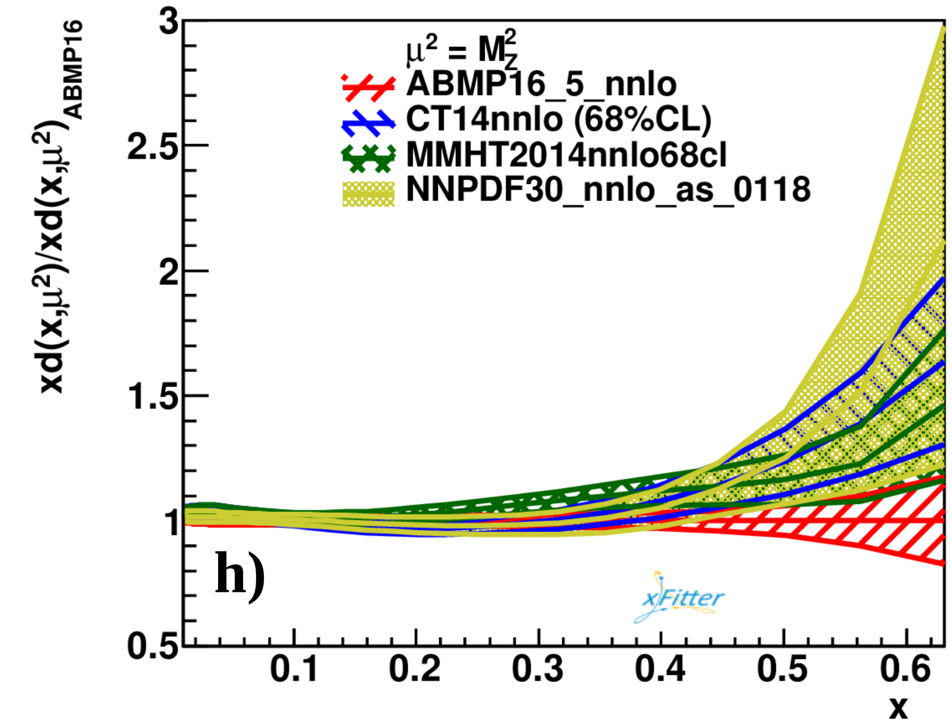

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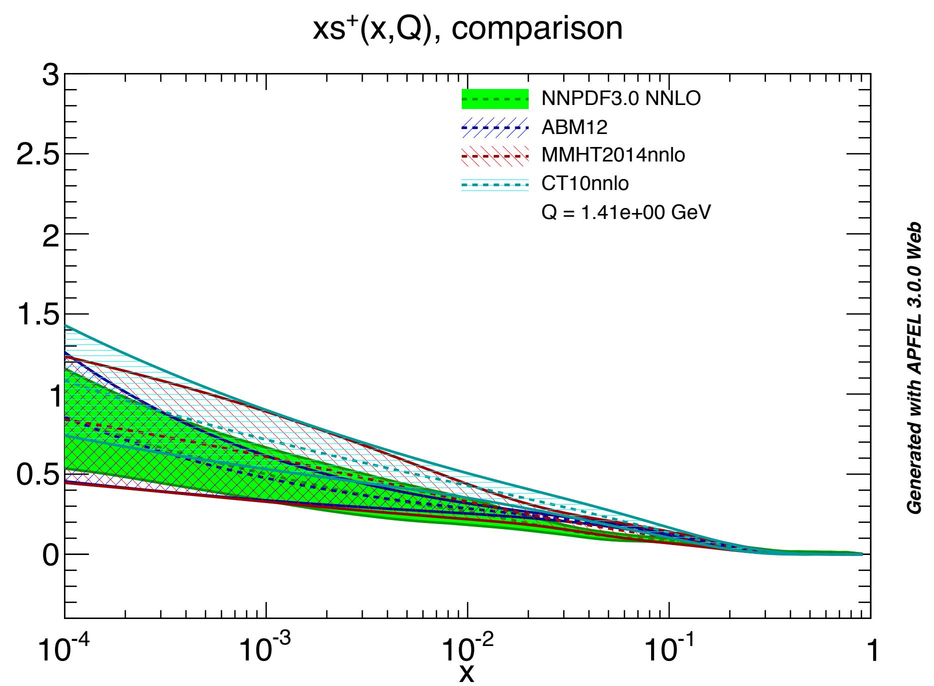
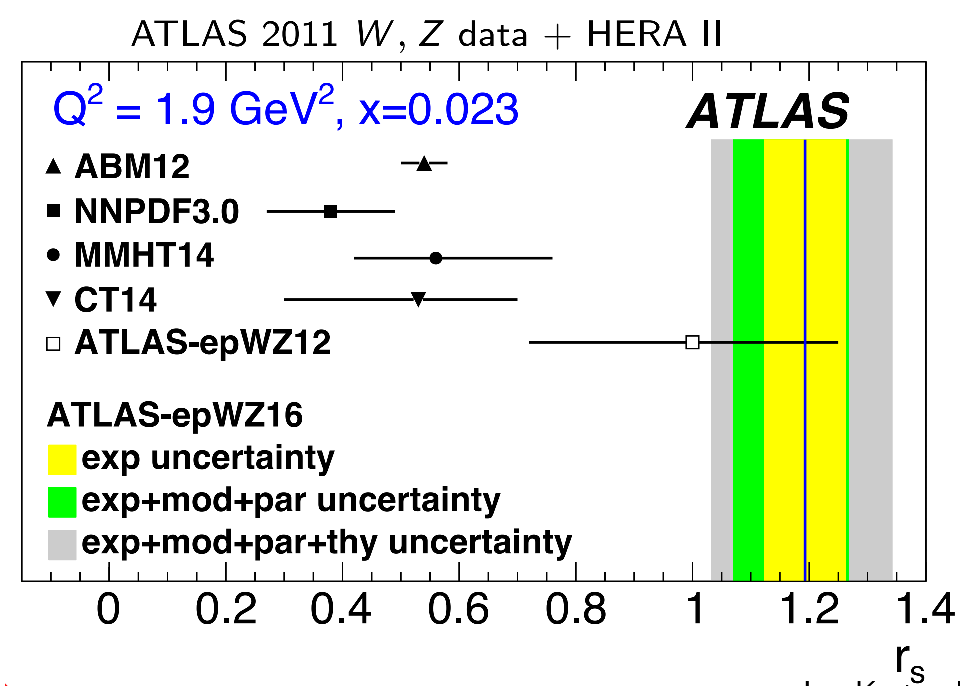
Strangeness in current PDF sets & the ATLAS W/Z data



Strangeness is one of the places where differences between current PDF sets is more marked, despite the fact that global fits use essentially the same data



Recent ATLAS W/Z measurement at odds with global fits that prefer suppressed strange-quark density

… possible tension with fixed-target data used in global fits (NuTeV, CCFR)

The SHiP experiment offers a unique opportunity

- NuTeV is the basic experiment
  - out of 1.280.000 nu_mu and 270.000 anti-nu_mu interactions

    NuTeV observed ~ 6000 dimuon events with:
    charm only form nu_mu and
    only charm decay to nu_mu

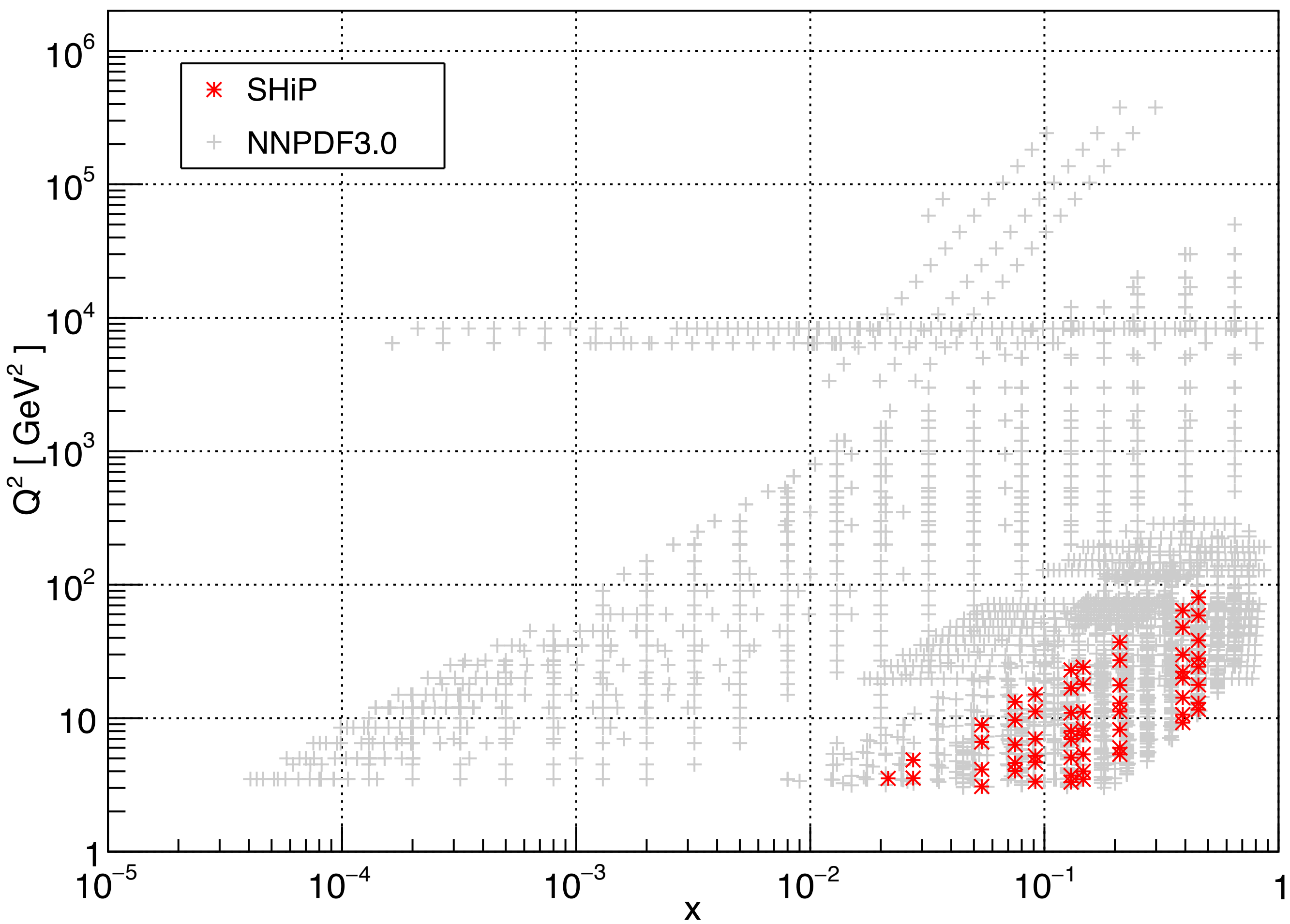
- SHiP would have more statistics
  nu_mu: 1.800.000
  anti-nu_mu: 660.000

  but should observe much more events of charm production, not only dimuon

70.000 from nu_mu	20.000 from anti-numu
+30.000 from nu_e	+ 30.000 from anti-nue
~100.000 charm	~ 50.000 anticharm

  - charm identification not limited kinematically
  - complementary information with respect to NuTeV (even closer to threshold)

Impact of SHiP measurements on strangeness



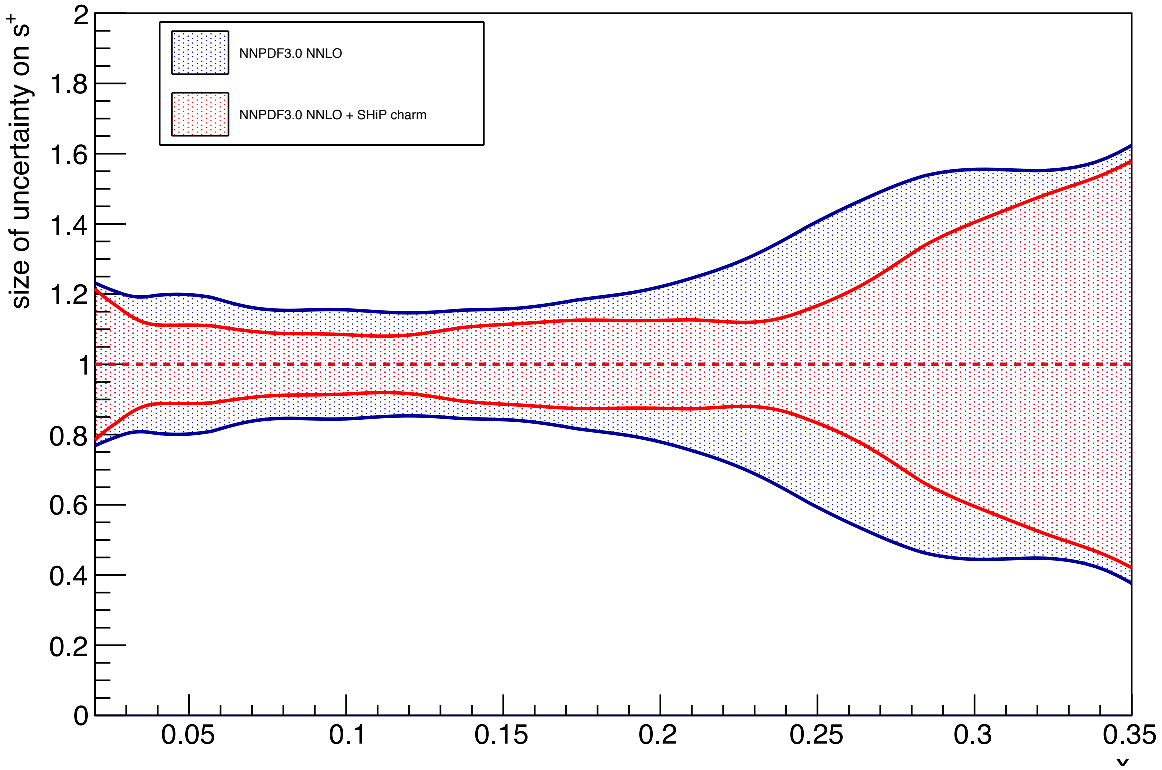
CC muon events only

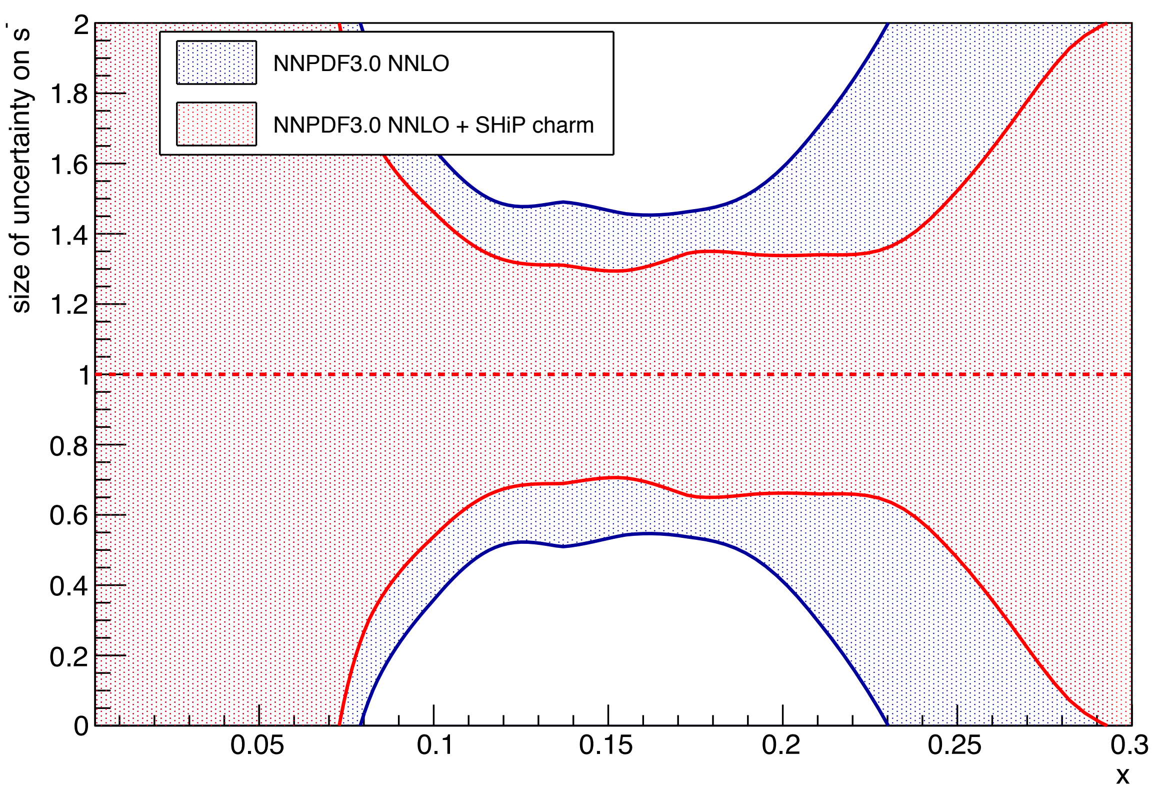
SHiP charm data cover the low-Q2/large-x region

Overlap and extend the kinematic coverage of NuTeV, at present the best probe of strangeness in global fits

Supersede the NuTeV data with respect to both statistical (larger dataset) and systematic (better understanding, full correlations available)uncertainties

Impact of SHiP measurements on strangeness





Assess the impact of adding SHiP pseudodata to NNPDF 3.0 performed using Bayesian reweighting

Pseudodata uncertainties:
~2-3% (charm) ~4-5% (anticharm) stat.
5% (uniform) uncorr. syst.

Significant reduction of the uncertainties on both the s^+ and s^- combinations in the medium-*x* range [0.005, 0.3]

Exotic baryons

* large number of newly discovered states

* neither can unambiguously be assigned to charmonia or bottomonia

  - X(3872) widely studied
  - still no interpretation
  - quantum number recently fixed by LHCb

From the PDG 2014

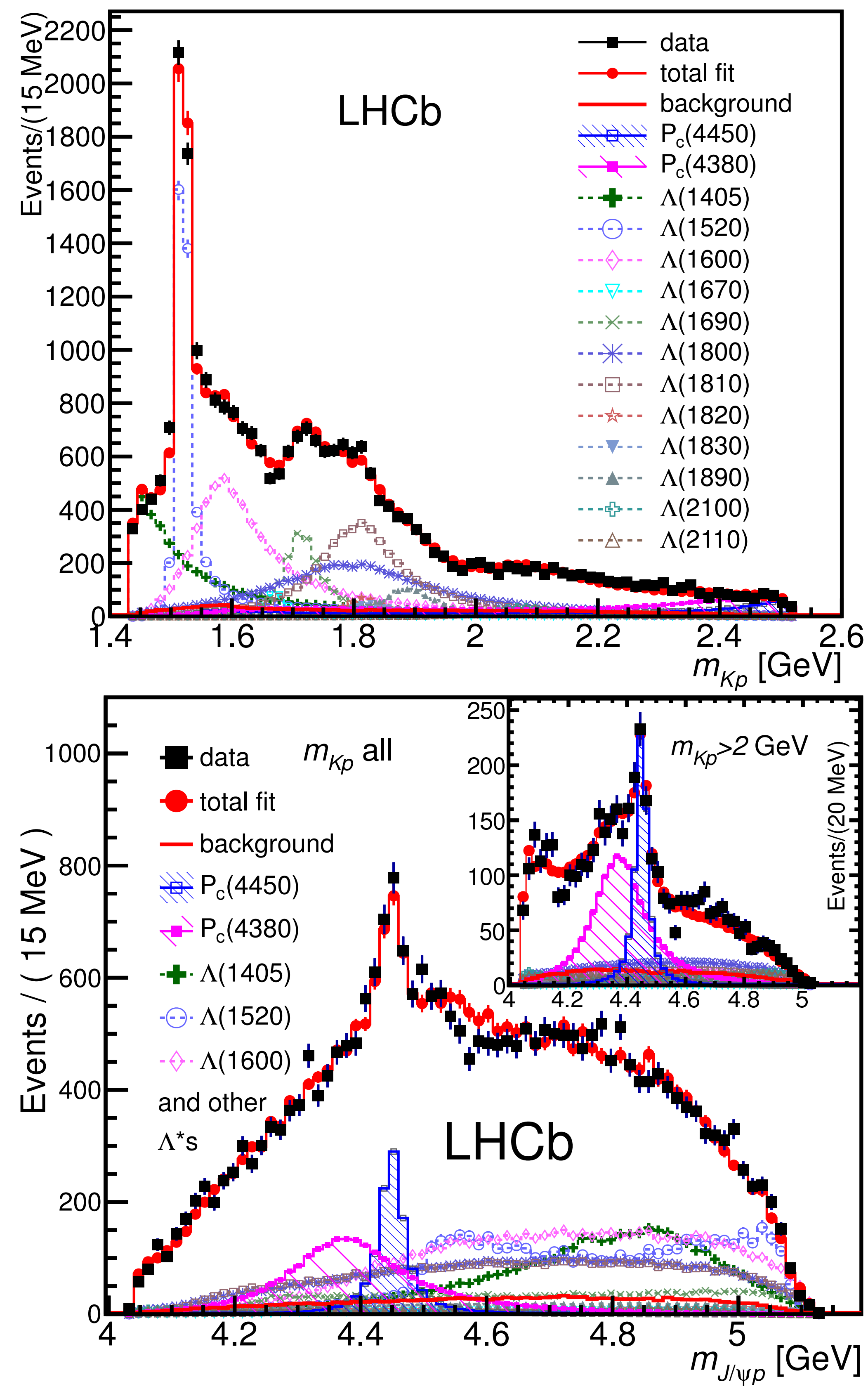
State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68±0.17	< 1.2	1^{++}	$B \to K\,(\pi^+\pi^- J/\psi)$	Belle [37,38] (12.8), BABAR [39] (8.6)	2003	OK
				$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$	CDF [40–42] (np), D0 [43] (5.2)		
				$B \to K\,(\omega J/\psi)$	Belle [44] (4.3), BABAR [45] (4.0)		
				$B \to K\,(D^{*0}\overline{D}^0)$	Belle [46,47] (6.4), BABAR [48] (4.9)		
				$B \to K\,(\gamma J/\psi)$	Belle [49] (4.0), BABAR [50,51] (3.6), LHCb [52] (>10)		
				$B \to K\,(\gamma\psi(2S))$	BABAR [51] (3.5), Belle [49] (0.4), LHCb [52] (4.4)		

* possibly a multiquark state

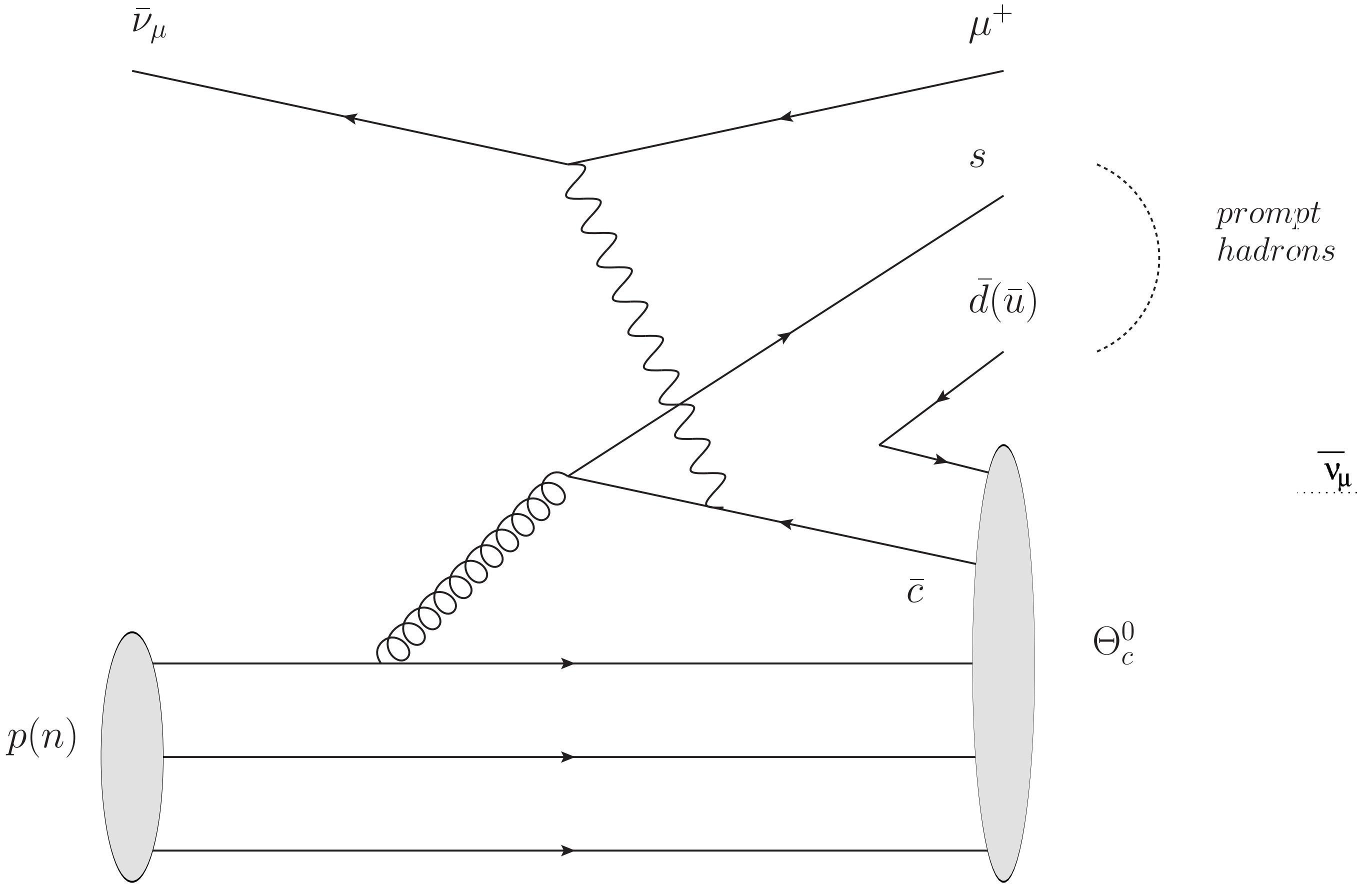
  - no limitation from the strong interaction
  - searches in the baryon sector might help to clarify the phenomenology

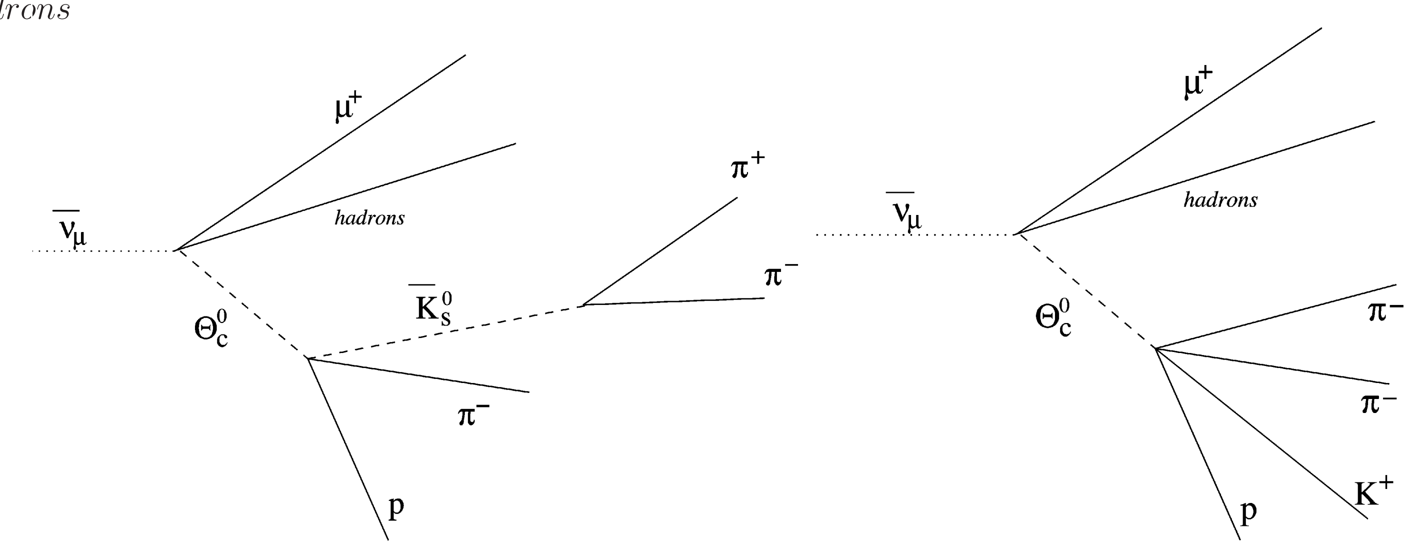
LHCb new resonances found in $\Lambda_b^0 \to J\psi p K^- \; (J\psi \to \mu^+\mu^-)$ decays

- two resonances (3/2-, 5/2+) or (3/2+, 5/2-)
- molecular models that seems appealing for mesons is challenged for barions (spin, parity)
- interpretation in terms of rescattering effects still cannot be ruled out
- other direct detection of pentaquark states desirable



Charmed Pentaquark





- an upper limit of about 2.8 GeV set to avoid strong decay into D^-p or D^0n
- production favored by the valence quarks available
- anti-nu scattering can generate a baryon with anti-charm content

CHORUS:

- Analyzed 2262 anti-nu-mu CC events finding no evidence
- 32 events with anti-charm found

$\sigma_{\Theta_c^0}/\sigma_{\bar{\nu}} < 0.039$ for $0.5\tau_{D^0}$

[De Lellis, Güler, Kawada, Köse, Sato, FT 2007]

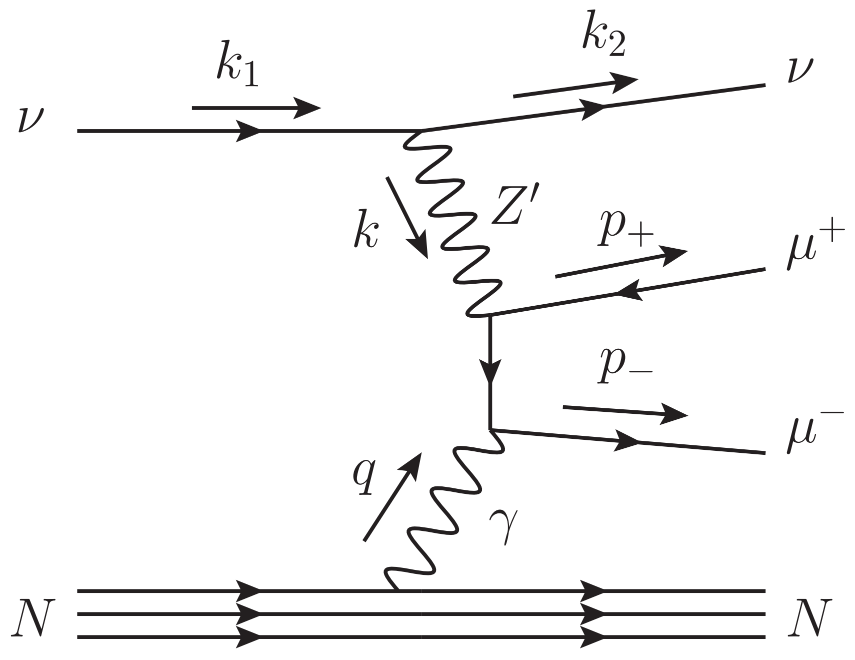
SHiP:

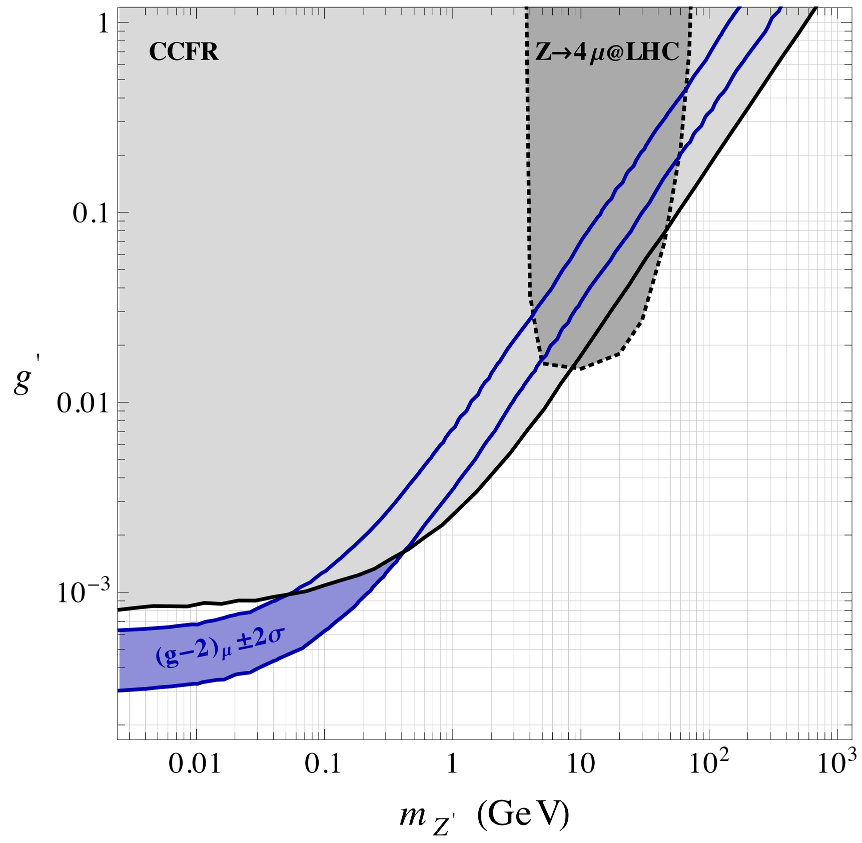
- 660.000 anti-nu-mu CC events expected
- ~ 50.000 events with anti-charm production expected

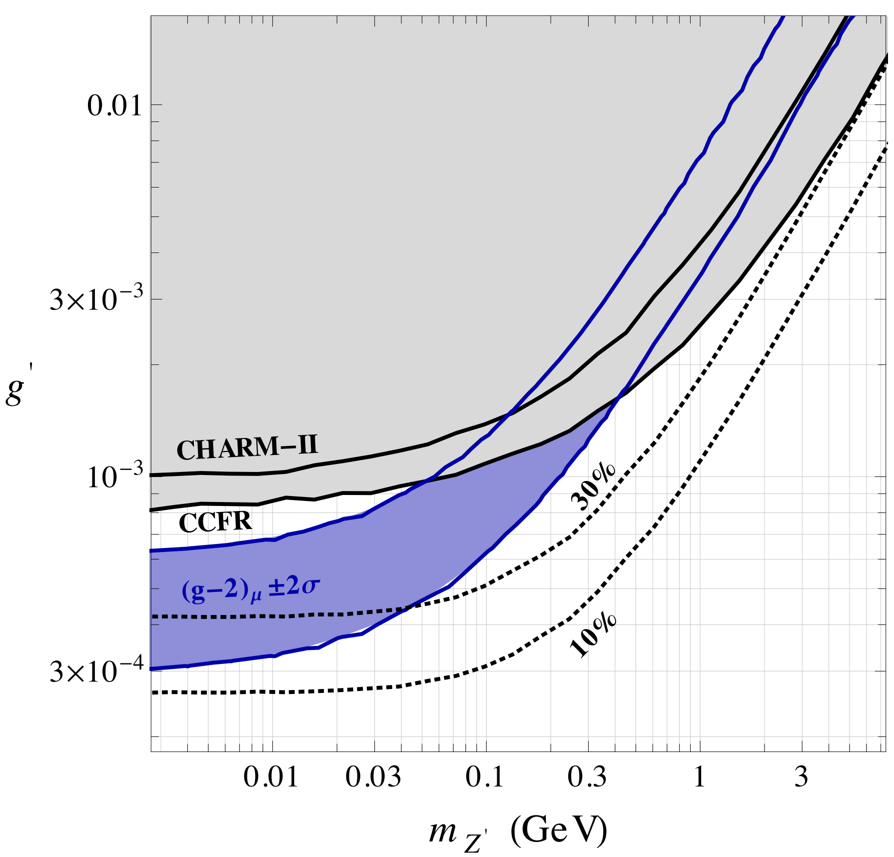
trident production

Associated production of charged leptons via neutral current interactions

[Altmannshofer, Gori, Pospelov, Yavin (2014)]







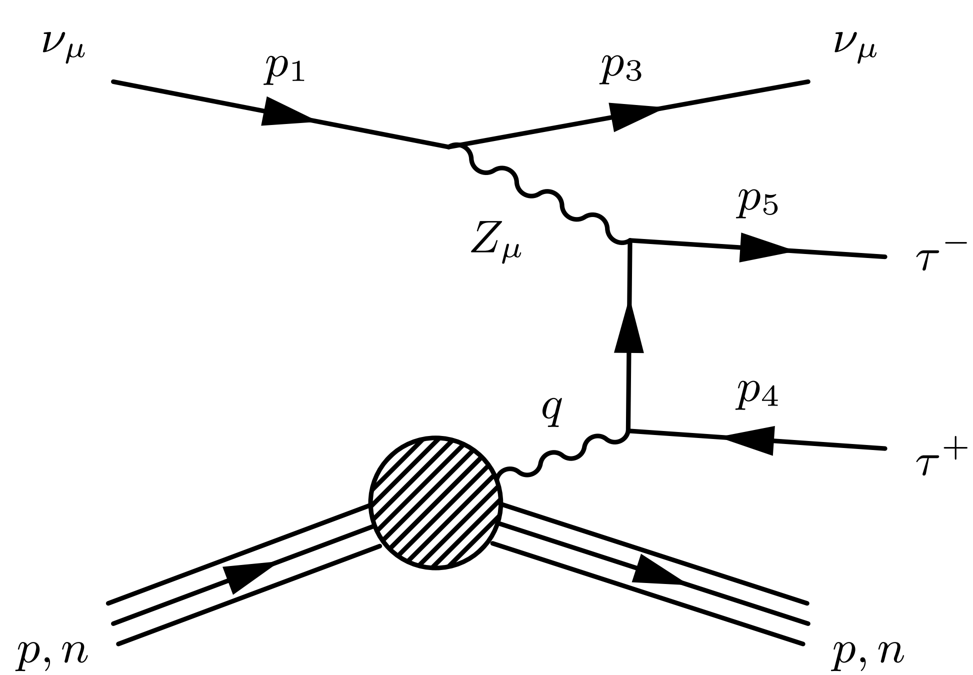
$$\sigma^{(\mathrm{SM+Z'})} = \sigma^{(\mathrm{SM})} + \sigma^{(\mathrm{inter})} + \sigma^{(\mathrm{Z'})}$$

$$\sigma^{(\mathrm{SM})} \simeq \frac{1}{2}\left(C_{\mathrm{V}}^2 + C_{\mathrm{A}}^2\right)\frac{2G_{\mathrm{F}}^2\alpha\, s}{9\pi^2}\left(\log\left(\frac{s}{m^2}\right) - \frac{19}{6}\right)$$

$m_{\mathrm{Z'}} \gg \sqrt{s}$	$\frac{\sigma^{(\mathrm{SM+Z'})}}{\sigma^{(\mathrm{SM})}} \simeq \frac{1+\left(1+4\sin^2\theta_{\mathrm{W}} + 2v_{\mathrm{SM}}^2/v_{\mathrm{Z'}}^2\right)^2}{1+\left(1+4\sin^2\theta_{\mathrm{W}}\right)^2}$	
$m_{\mathrm{Z'}} \ll \sqrt{s}$	$\sigma^{(\mathrm{inter})} \simeq \frac{G_{\mathrm{F}}}{\sqrt{2}}\frac{g'^2 C_{\mathrm{V}}\alpha}{3\pi^2}\log^2\left(\frac{s}{m^2}\right)$	$m \ll m_{\mathrm{Z'}} \ll \sqrt{s}$: $\sigma^{(\mathrm{Z'})} \simeq \frac{1}{m_{\mathrm{Z'}}^2}\frac{g'^4\alpha}{6\pi^2}\log\left(\frac{m_{\mathrm{Z'}}^2}{m^2}\right)$ $m_{\mathrm{Z'}} \ll m \ll \sqrt{s}$: $\sigma^{(\mathrm{Z'})} \simeq \frac{1}{m^2}\frac{7g'^4\alpha}{72\pi^2}\log\left(\frac{m^2}{m_{\mathrm{Z'}}^2}\right)$

Associated production of charged leptons via neutral current interactions

[Magill, Plastid (2016)]

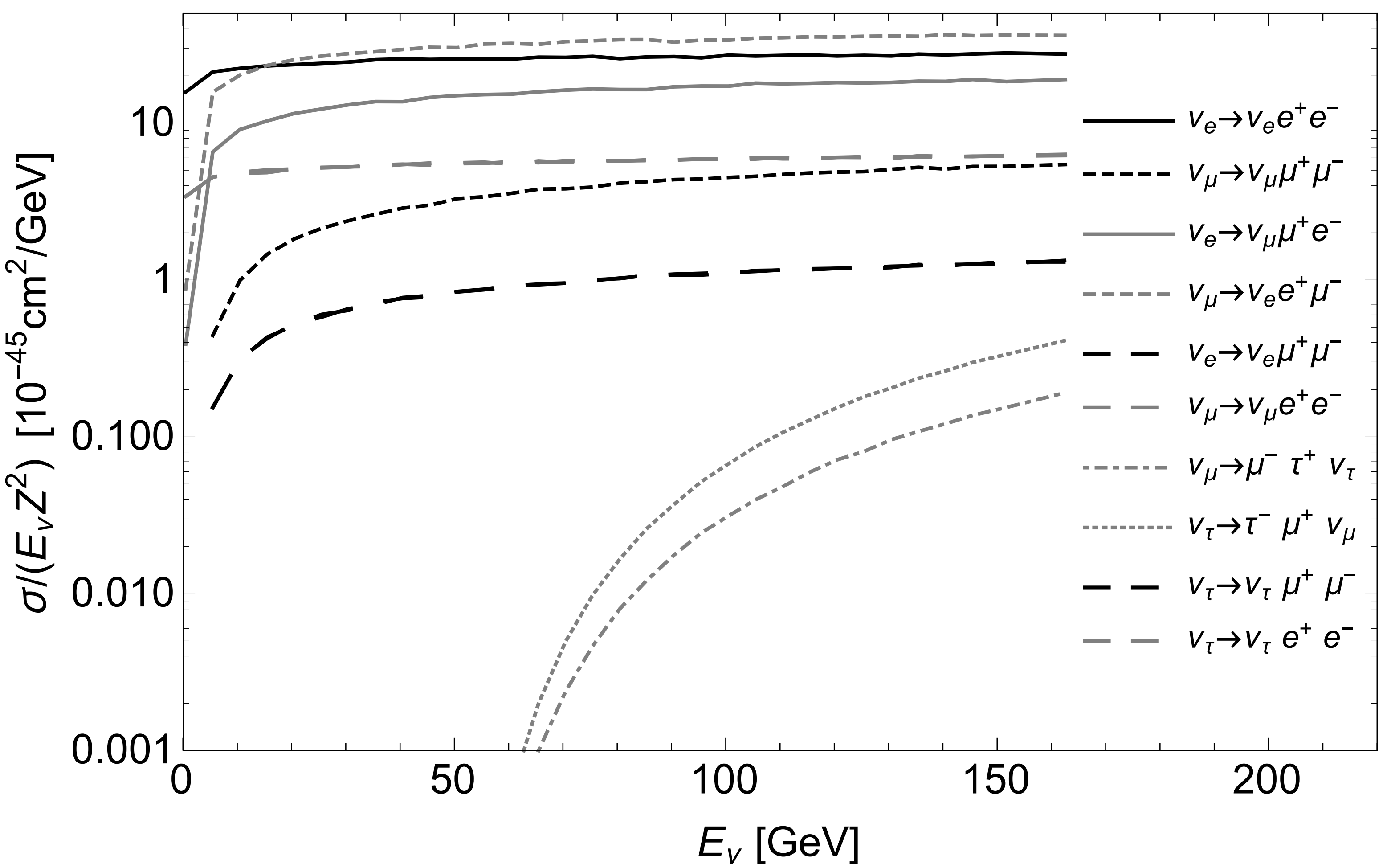


tau+ tau- generation possible but dominant mode is $\nu_\mu \to \nu_e \mu^- e^+$

- CC-exclusive process (high axial-vector couplings)
- large flux of muon neutrinos
- logarithmic enhancement afforded by the low electron mass.

Associated production of charged leptons via neutral current interactions

[Magill, Plastid (2016)]



Neutrino Beam			Anti-Neutrino Beam		
Process	Coh	Diff	Process	Coh	Diff
$\nu_\mu \to \nu_e e^+ \mu^-$	85.46	24.6	$\bar{\nu}_\mu \to \bar{\nu}_e e^- \mu^+$	29.96	9.61
$\nu_\mu \to \nu_\mu e^+ e^-$	28.28	5.32	$\bar{\nu}_\mu \to \bar{\nu}_\mu e^+ e^-$	22.48	3.58
$\nu_e \to \nu_e e^+ e^-$	21.69	2.95	$\bar{\nu}_e \to \bar{\nu}_e e^+ e^-$	15.65	2.45
$\nu_e \to \nu_\mu \mu^+ e^-$	9.1	2.31	$\bar{\nu}_e \to \bar{\nu}_\mu \mu^- e^+$	14.31	3.16
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	4.79	3.01	$\bar{\nu}_\mu \to \bar{\nu}_\mu \mu^+ \mu^-$	3.76	2.38
$\nu_e \to \nu_e \mu^+ \mu^-$	0.42	0.16	$\bar{\nu}_e \to \bar{\nu}_e \mu^+ \mu^-$	0.3	0.12
$\nu_\tau \to \nu_\tau e^+ e^-$	0.13	0.03	$\bar{\nu}_\tau \to \bar{\nu}_\tau e^+ e^-$	0.13	0.02
$\nu_\tau \to \nu_\tau \mu^+ \mu^-$	0.01	0.	$\bar{\nu}_\tau \to \bar{\nu}_\tau \mu^+ \mu^-$	0.01	0.
$\nu_\tau \to \tau^- \mu^+ \nu_\mu$	0.	0.01	$\bar{\nu}_\tau \to \tau^+ \mu^- \bar{\nu}_\mu$	0.	0.
$\nu_\mu \to \mu^- \tau^+ \nu_\tau$	0.	0.23	$\bar{\nu}_\mu \to \mu^+ \tau^- \bar{\nu}_\tau$	0.	0.39
Total	149.88	38.62		86.6	21.71

Conclusion

- Experiments at the intensity frontier provide excellent tests for Standard Model
- I’ve shown several examples for the neutrino detector in SHiP
- Remarkably, today tau neutrino and antineutrino are the less known among the elementary particles in the SM
- Measurements and predictions are quite challenging but doable and could bring the unexpected!