CHARMONIUM MEASUREMENTS WITH AMBER – A TOOL FOR ACCESSING THE MESON PDFS

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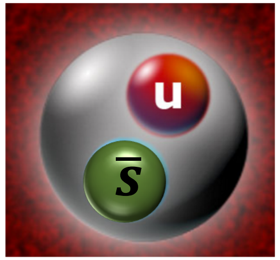
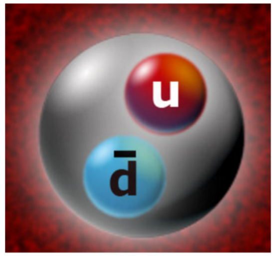
ON BEHALF OF THE COMPASS++/AMBER COLLABORATION

(WITH INPUT FROM W.-C. CHANG, J.-C. PENG, T. SAWADA, P. FACCIOLI)

MESON STRUCTURE AND THE ORIGIN OF HADRON MASSES

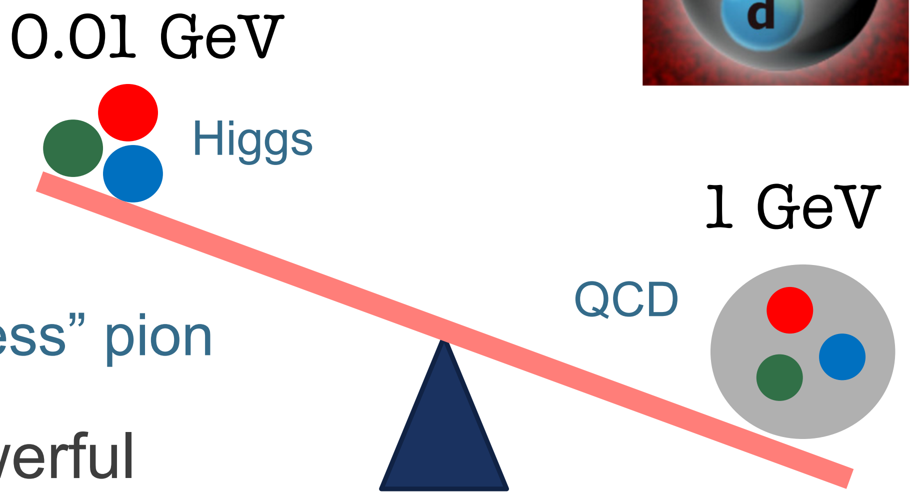
Contrary to nucleon, the meson structure is nearly unknown





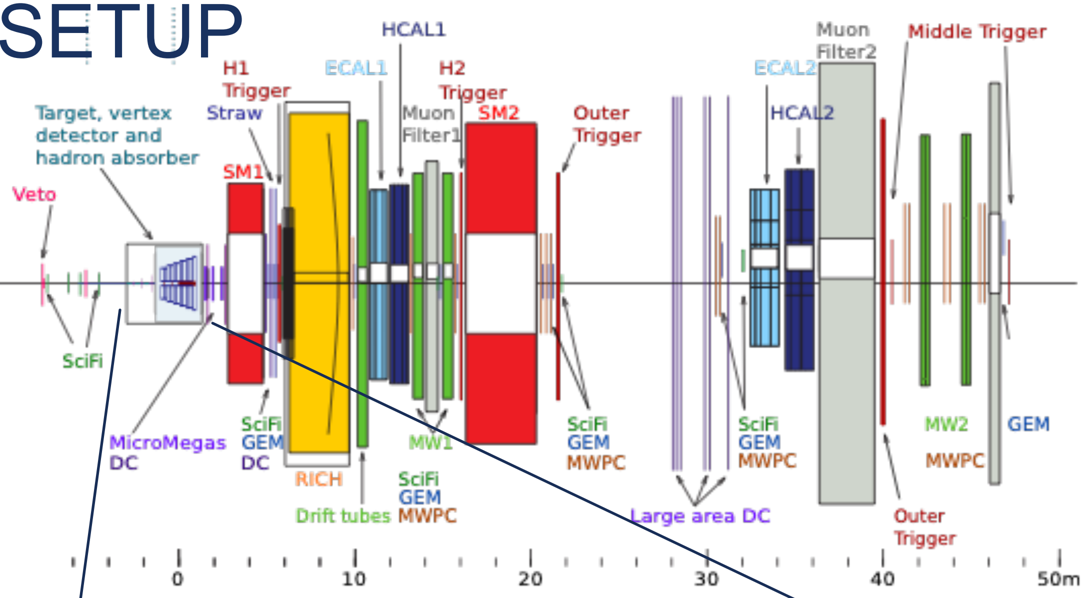
- Meson structure
  - What is the behavior of the kaon and pion PDFs vs the PDFs in the nucleon?
  - The s quark in the kaon is heavier: Are kaon and pion gluon PDFs identical?

- Understand the hadron mass budget
  - Higgs mechanism can't explain hadron masses
  - Need to explain the "heavy" nucleon and the "massless" pion

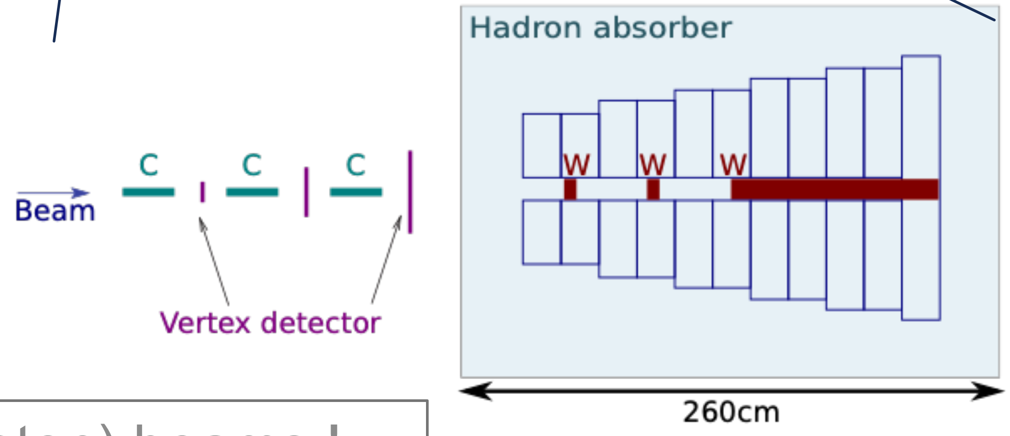


- My talk: charmonium production could prove a powerful tool for accessing the π/K PDFs

AMBER EXPERIMENT – PROPOSED SETUP



- Run 3: 2022 – 2024
  - ➢ positive beam: pions (25%), protons (74%)
  - ➢ negative beam: pions (97%), kaons (2%)
- Run 4 (with RF): > 2026
  - ➢ negative kaons (~50%), pions (~50%)
  - ➢ positive kaons
  - ➢ antiprotons



Only place in the world with pion and (kaon, antiproton) beams !

DIMUON STUDIES IN COMPASS++/AMBER

- Run 3: 2022 – 2024
  - E = 190 GeV, positive and negative hadron beams
  - light (^{12}C) and heavy (^{184}W) targets
  - Simultaneous measurements: π^+ and p, and also π^-

DY data: see talk by M. Quaresma

- Run 4:
  - strongly relies on RF separated beams
  - E < 100 GeV, positive and negative beams
  - New, highest-ever statistics measurements with K^+, K^-, antiprotons …

Note that: Drell-Yan and charmonium data are collected in parallel

CHARMONIUM WITH AMBER

- Advantages of (our) FT energies: 100 – 200 GeV
  - J/ψ has large cross sections – factor of 30-40 larger than Drell-Yan at 190 GeV
  - Fixed-target energies: production is dominated by 2 -> 1 processes
  - Can measure x_F, p_T, λ distributions with unprecedented statistics (> 1 M events)
  - Collect also ψ' data, together with J/ψ

- Present status of FT measurements
  - Meson FT data come from CERN and Fermilab experiments: mostly 80's, 90's
  - No new FT data since nearly two decades – contrary to charmonium collider data

CHARMONIUM WITH AMBER

- Difficulties – and impetus for deeper studies
  - Model dependence: the production mechanism is not well known. A long history…
  - Mainly two production models: CEM and NRQCD. At FT energies, both models have $q\bar{q}$ and gg as dominant contributions to the cross section
  - $p_T \leqslant M(J/\psi)$: complementary to LHC, where $p_T >> M(J/\psi)$
- Huge potential interest
  - Add meson-induced FT data to charmonium production studies at colliders
  - Access quark/gluon PDFs of pion and kaon
  - Access gluon PDFs in nuclei…

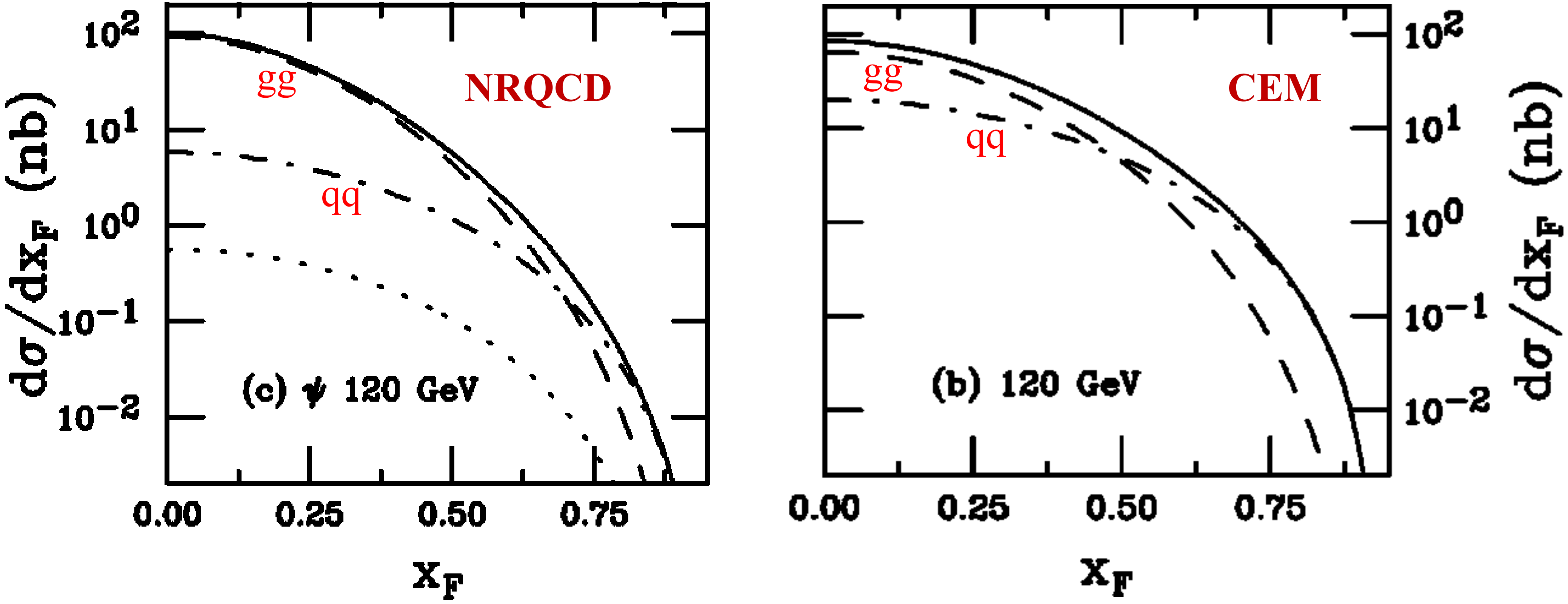
J/ψ PRODUCTION MECHANISMS

- Color Evaporation Model (CEM)
  - Simple cross section for producing $Q\bar{Q}$ pairs. Ignores quantum numbers.
  - Considerable phenomenological success
- Recent improvements: Improved CEM (ICEM) (Cheung and Vogt, PRD98,2018)
  - includes p_T dependence, ICEM + k_T factorization => cross sections, x_F and p_T dependence, polarization, etc…
- NRQCD (Bodwin, Braaten, Lepage): rigorous consequence of QCD
  - Long-Distance Matrix Elements (LDME): probability of the *cc* pair to evolve into a quarkonium state. LDME: conjectured to be universal, ….

DO WE UNDERSTAND THE J/ψ PRODUCTION?

➢ Two models at NLO: CEM and NRQCD

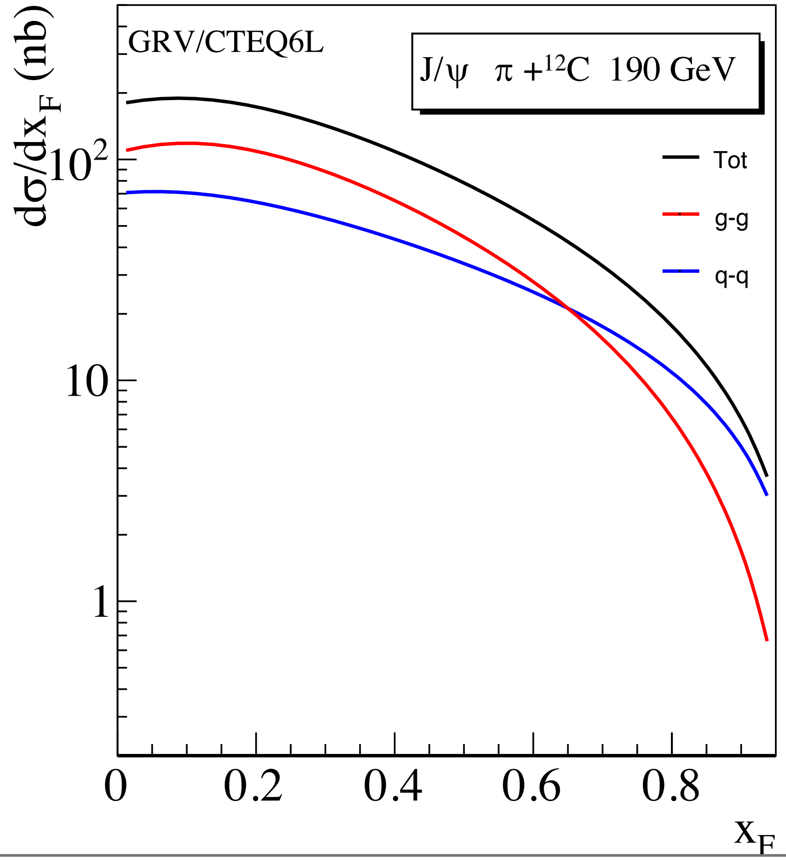
(R.Vogt, 2000)



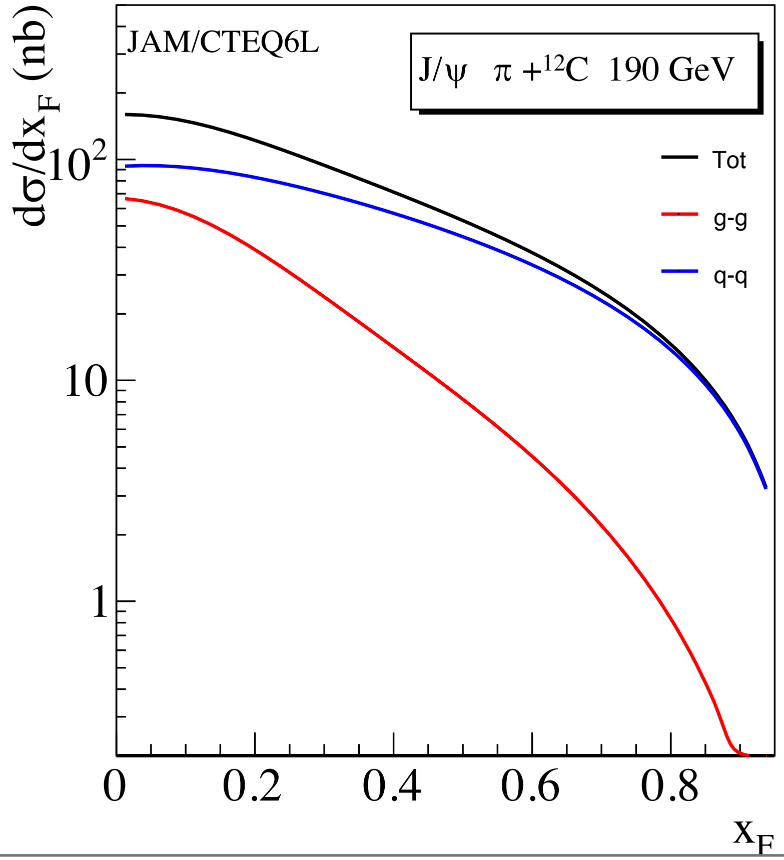
Qualitatively similar, but quantitatively different results

π + ^{12}C CROSS SECTION FOR TWO PDF "GLOBAL" FITS (CEM AT LO)

π PDF: GRV (1992)

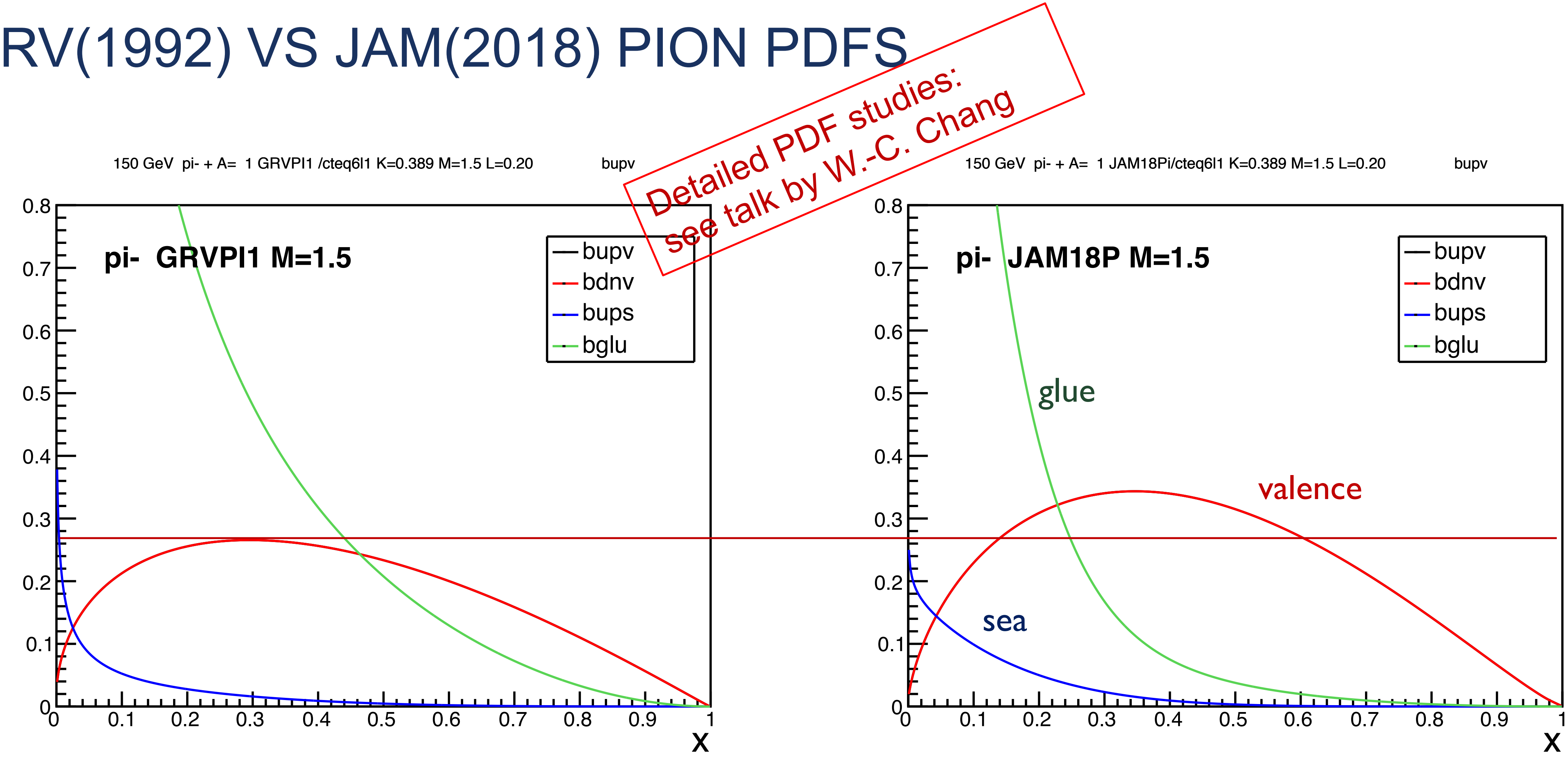


π PDF: JAM (2018)



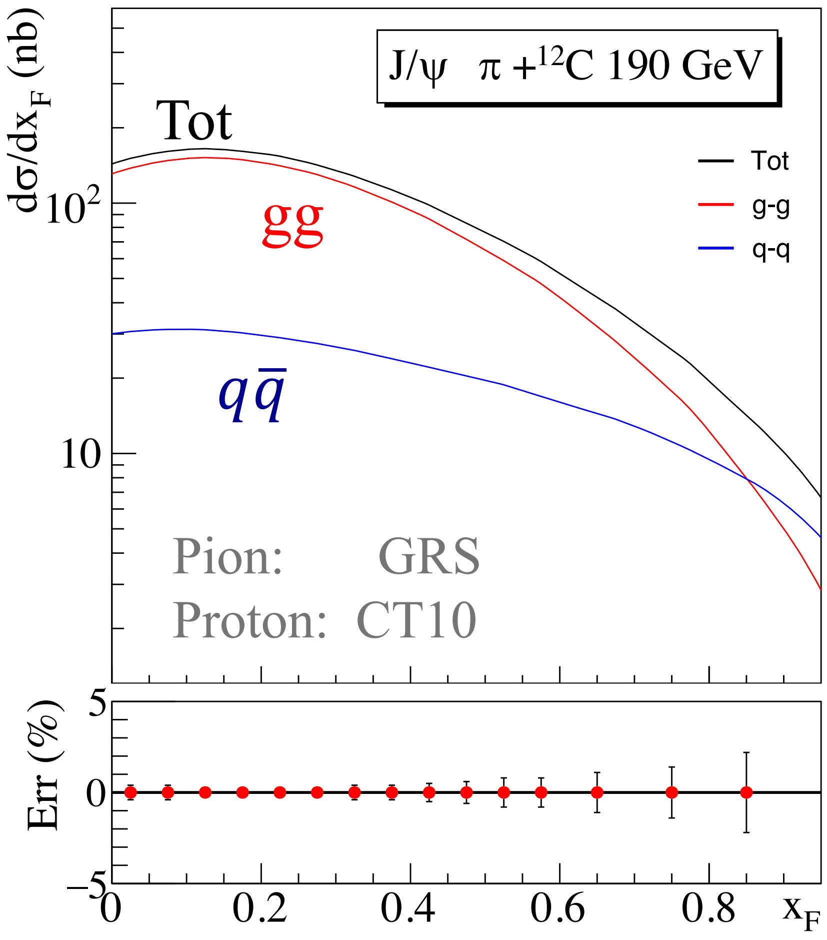
Could J/ψ data be used to infer meson PDFs ?

GRV(1992) VS JAM(2018) PION PDFS



The two global fits lead to different PDFs: valence, gluon, sea

ICEM PREDICTIONS – X_F DEPENDENCE



ICEM: Cheung and Vogt, PRD98,114029 (2018) and priv. comm.

Relative statistical errors (%!)

POLARIZATION

- J/ψ is a 1^{--} particle; its third component is $J_z = 0, +1, -1$.
  - α = +1 : 100% transverse polarization ($J_z = \pm 1$)
  - α = 0 : unpolarized
  - α = -1 : 100% longitudinal polarization ($J_z = 0$)

$$\frac{d\sigma}{d(\cos\theta)} \propto 1 + \alpha \cos^2\theta,$$

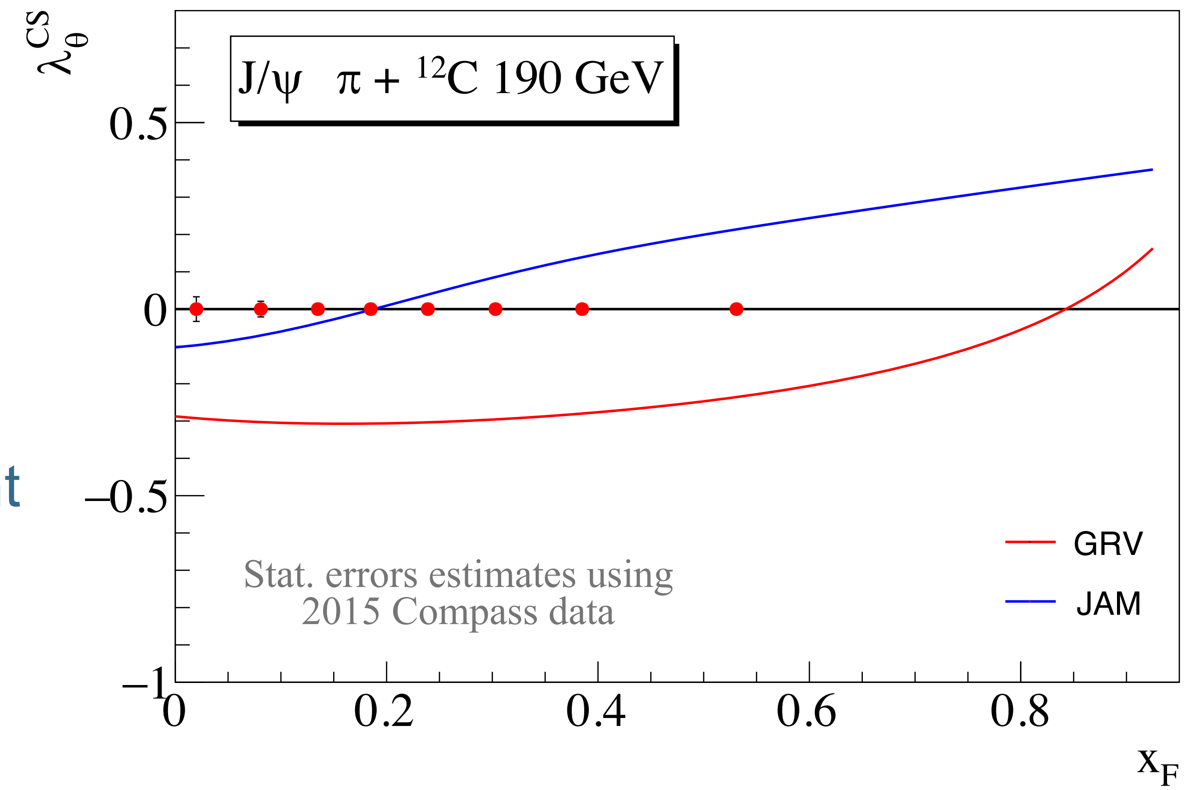
- Polarization is a fundamental observable
  - angular momentum, chirality, parity conservations preserve the properties of the J/ψ: from production to the 2μ decay
  - Nature wants to help us, for $q\bar{q}$: $\alpha \simeq +1$, but for gg: $\alpha \simeq -1$
  - Key variable for understanding the bound state formation

POLARIZATION: EXPECTED RESULTS (CHEUNG AND VOGT, PRIV. COMM.)

- ICEM xF-dependent predictions
  - with minimal model-dependence

$$\lambda_\vartheta^{CS} \approx +0.4 \text{ for } q\bar{q}$$
$$\lambda_\vartheta^{CS} \approx -0.6 \text{ for } gg$$

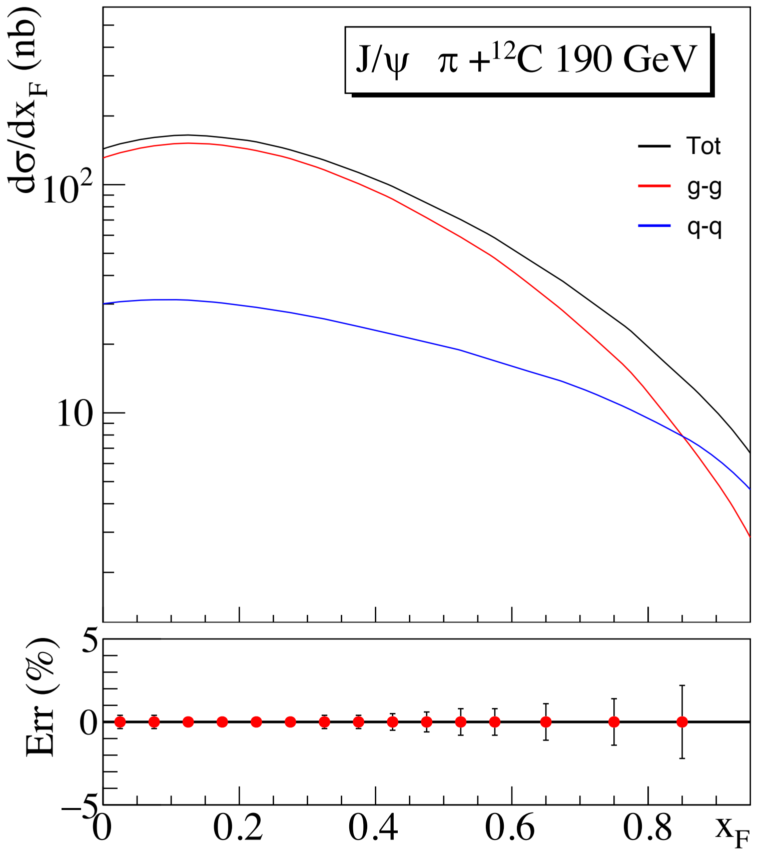
  - The difference between the two predictions results from the different amount of $q\bar{q}$ and gg contributions as a function of x_F.



The polarization value as a function of x_F is ALSO sensitive to the shape differences between gg and $q\bar{q}$ contributions to the cross section

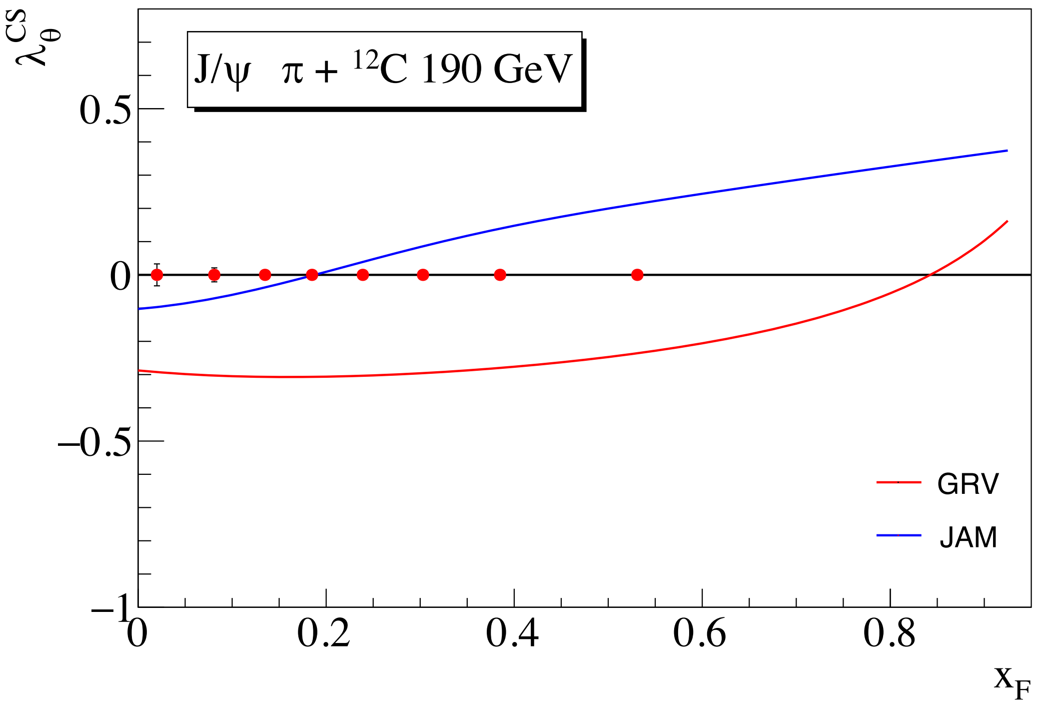
J/Ψ MEASUREMENTS AT COMPASS++/AMBER

Cross section (ICEM)



Polarization (ICEM)

ICEM: CHEUNG AND VOGT, PRIV. COMM.



Multidimensional analysis of both cross section and dilepton decay angles should provide constraint on the gg and $q\bar{q}$ fractions

ESTIMATED J/ψ STATISTICS

Experiment	Target type	Beam energy (GeV)	Beam type	J/ψ events
NA3 [76]	Pt	150	π^-	601000
		280	π^-	511000
		200	π^+	131000
			π^-	105000
E789 [127, 128]	Cu	800	p	200000
	Au			110000
	Be			45000
E866 [129]	Be Fe Cu	800	p	3000000
NA50 [130]	Be	450	p	124700
	Al			100700
	Cu			130600
	Ag			132100
	W			78100
NA51 [131]	p	450	p	301000
	d			312000
HERA-B [132]	C	920	p	152000
This exp	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

Comments

Cross sections not published, only plots available

x_F and p_T cross sections available

Only ratios of cross sections available

Only A-dependent studies of total cross sections

Only A-dependent studies of total cross sections

x_F and p_T cross sections available

…

Estimations based on Compass preliminary numbers

ψ' PRODUCTION

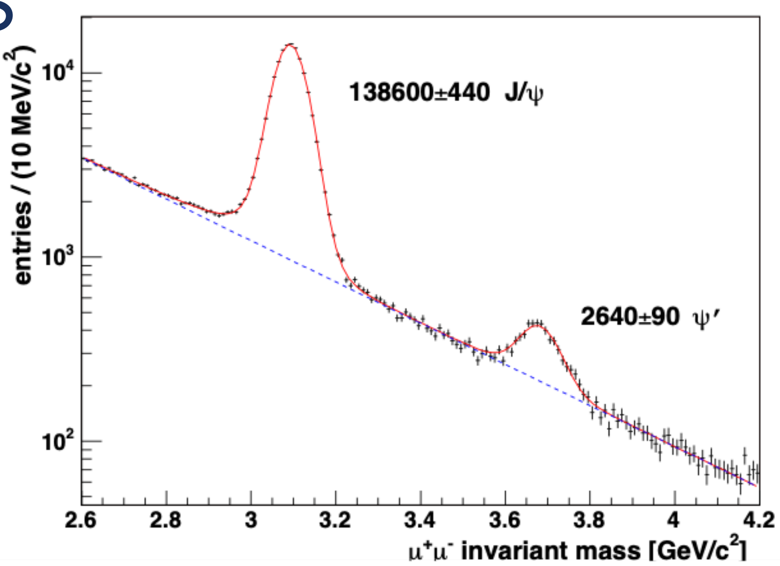
- Advantages
  - No feed-down contributions. Consequences:
    - straightforward test of production models, no dilution.
    - $q\bar{q}$ and gg contributions could reach their maximum polarization values
  - x_F and p_T dependences could be measured altogether with the polarization
  - AMBER could provide the largest ψ' data set ever.
- Requirements
  - Good mass resolution (≤ 100 MeV) to separate J/ψ and ψ' – vertex detectors
  - Alternative: dedicated run for charmonium studies without absorber – much improved resolution, but significantly lower statistics.

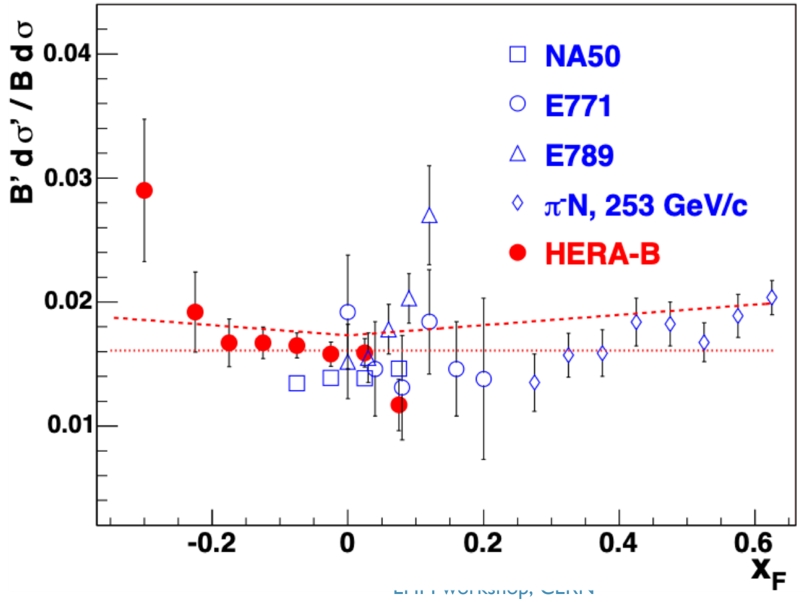
ψ' PRODUCTION – EXPECTED STATISTICS

- From previous measurements (e.g. HERA-B, 2007)
  - R (ψ'/J/ψ) ≃ 0.018 (used to estimate nb of ψ')

Target	Energy	Beam	Nb of ψ'
^{12}C	190 GeV	π^+	21 600
		π^-	32 400
		p	27 000
^{184}W		π^+	9 000
		π^-	12 600
		p	12 600

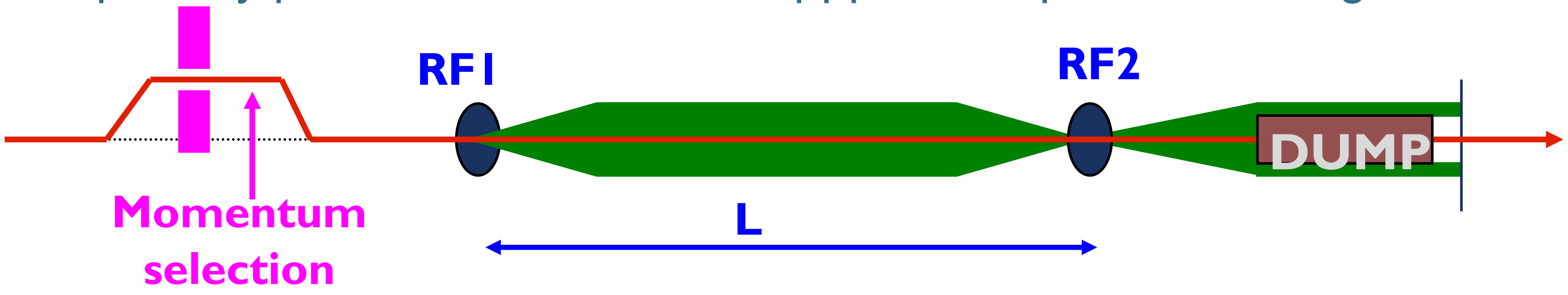
An order of magnitude better than previous experiments !





RUN4++ : RF SEPARATED BEAMS – HIGH-INTENSITY

- Studies underway at CERN for RUN4 (2026++)
- Some assumptions:
  - L = 450 m, f = 3.9 GHz, beam spot within 1.5 mm
  - Reasonable primary target efficiency, 80% wanted particles pass dump
  - Number of primary protons: 100 - 400x10^{11} ppp on the production target



  - Energy limitation : $\lesssim$ 100 GeV

Large improvement in kaon and antiproton intensities (> x 20- 40 !)

PROTON AND ANTIPROTON-INDUCED J/Ψ PRODUCTION

- $p(\bar{p}) + p$ charmonium cross sections

$$\bar{p}(\bar{u}\bar{u}\bar{d}) + p(uud) \propto gg + [\bar{u}_v u_v + d_v d_v] + [\bar{u}_v u_s + \bar{d}_v d_s] + [\bar{u}_s u_v + \bar{d}_s d_v] + \text{sea} - \text{sea terms}$$

$$p(uud) + p(uud) \propto gg + [------ -] + [\bar{u}_s u_v + \bar{d}_s d_v] + [u_v \bar{u}_s + d_v \bar{d}_s] + \text{sea} - \text{sea terms}$$

- Difference of the $\bar{p}$ and p-induced cross sections:

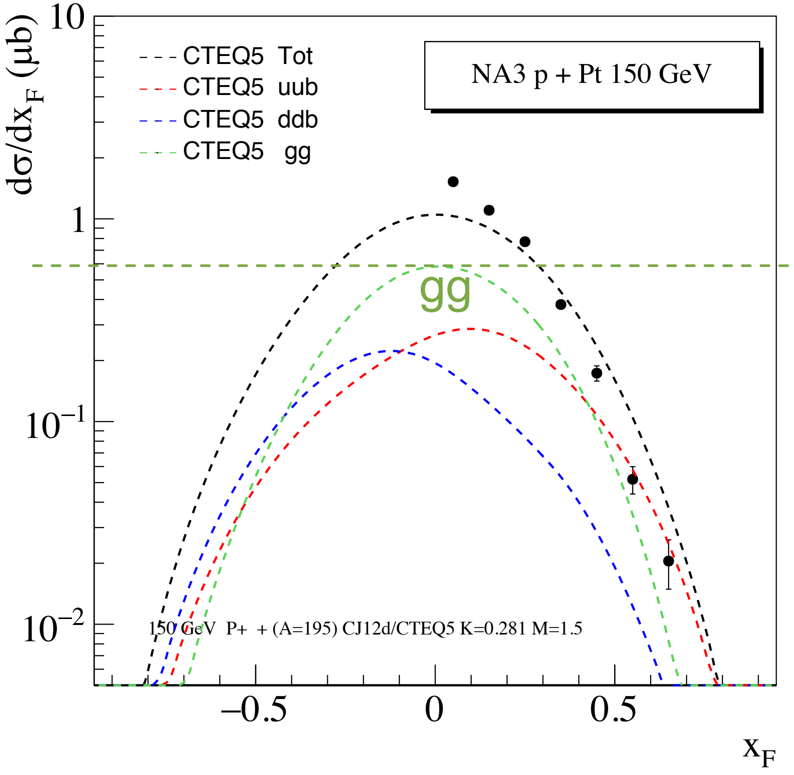
$$\sigma(\bar{p}) - \sigma(p) \propto [\bar{u}_v u_v + d_v d_v]$$

➢ Note that the proton PDFs are very well known.

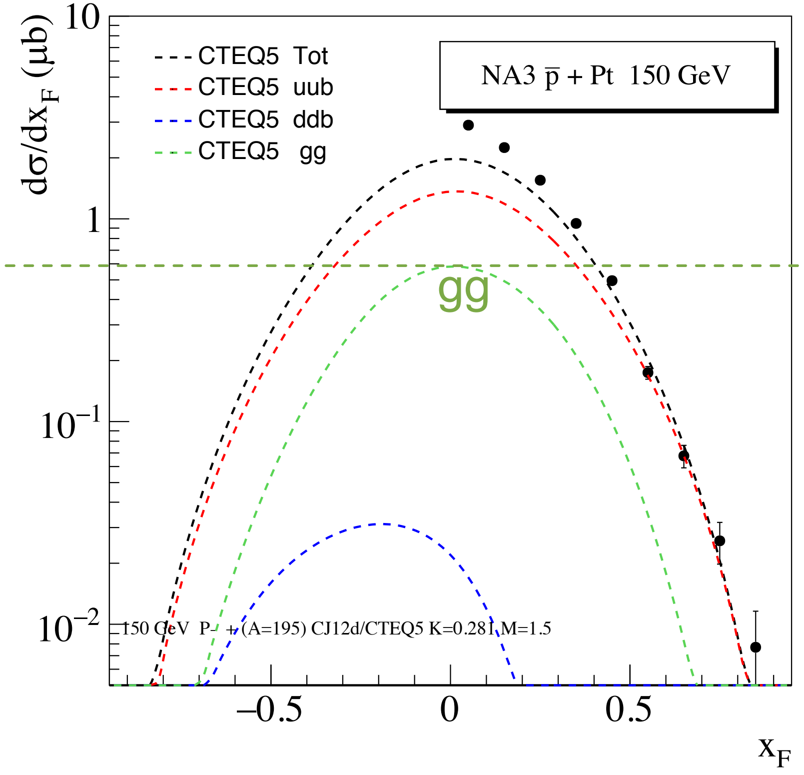
The cross section difference could serve as a benchmark for the J/ψ production mechanism

NA3@150 GEV: COMPARISON PROTON VS ANTIPROTON (CEM)

proton beam on a Pt target
no valence-valence quark term



antiproton beam
with valence-valence quark term



The (largest) valence-valence term is only present in antiproton-induced production

J/ψ – MODEL-INDEPENDENT ACCESS TO THE KAON VALENCE PDF!

- Production cross section for K⁺ and K⁻

$$K^-(\bar{u}s)+p(uud)\propto gg+\left[\bar{u}_v^K u_v^p\right]+\left[\bar{u}_v^K u_s^p+s_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

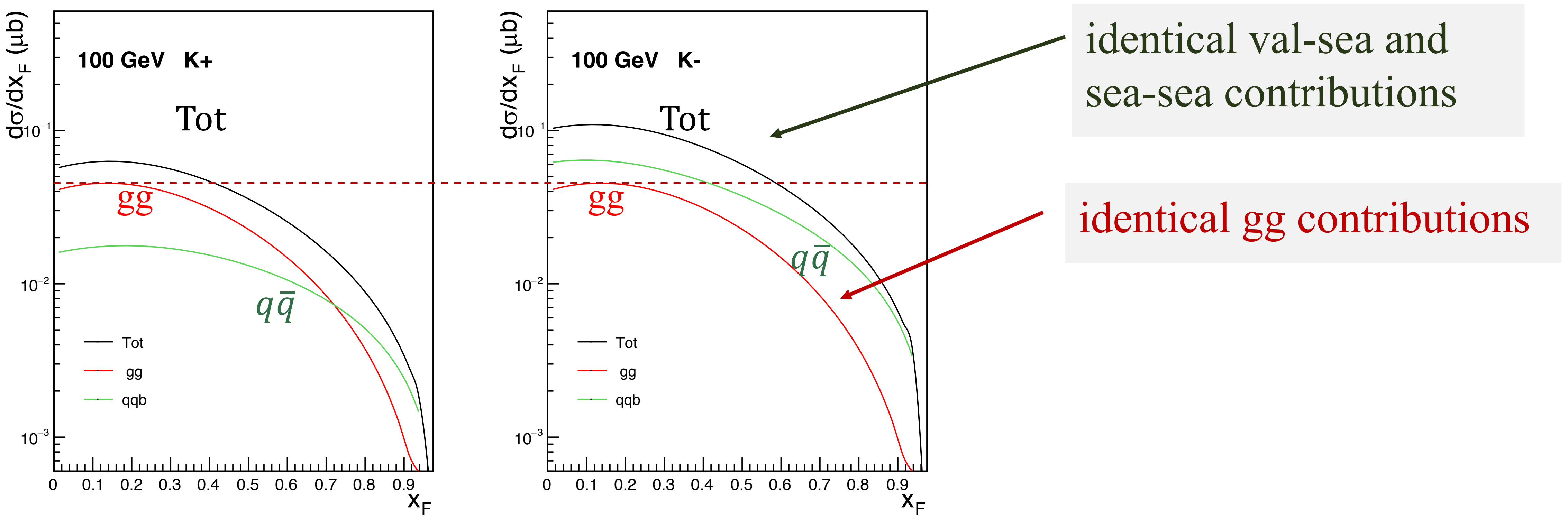
$$K^+(u\bar{s})+p(uud)\propto gg+\left[---\right]+\left[u_v^K\bar{u}_s^p+\bar{s}_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

val-val | val-sea | sea-val | sea-sea

- The cross section difference isolates the val-val term: $\sigma(K^-)-\sigma(K^+)\propto\bar{u}_v^K u_v^p$
  - ✓ Can be compared with the kaon valence PDF determined using Drell-Yan
  - ✓ For E < 100 GeV, the $q\bar{q}$ contribution is dominant

KAON-INDUCED J/ψ PRODUCTION – CEM AT 100 GEV

LO CEM calculations

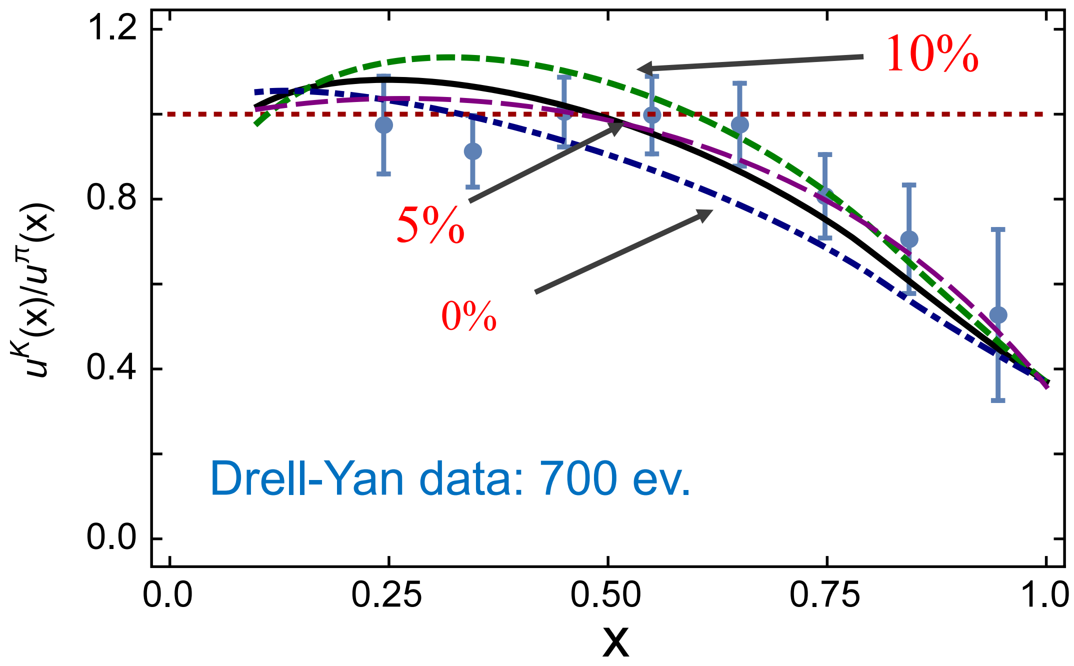


$K^- - K^+$ difference provides alternative (to DY) way to access the kaon valence PDF

KAON VALENCE PDF

DSE calculation

Chen et al., PRD 93, 074021 (2016).



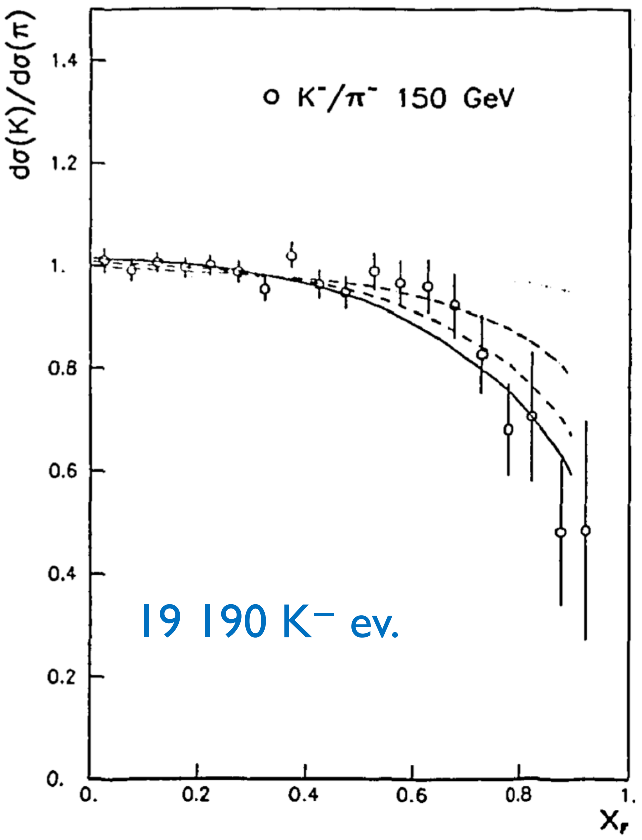
gluon 1st moment

DSE: at the hadronic scale gluons carry
5% of the momentum of the kaon BUT
30% of the momentum of the pion !

700 DY events only. But the number of J/ψ events is much larger ….

J/Ψ DATA ON THE KAON: STATISTICS

NA3 K^-/π^- J/ψ RATIO



AMBER: nb of expected K (*using LoI DY conditions – with RF)

Expt	Tgt	E(GeV)	Beam	Nb of J/ψ
WA39	^{184}W	40	K^-	$\lesssim$100
NA3	^{195}Pt	150	K^-	19 190
AMBER	^{12}C	100	K^-	$\simeq$ 1 000 000
AMBER		100	π^-	$\simeq$ 2 000 000
WA39	^{184}W	40	K^+	$\lesssim$100
NA3	^{195}Pt	200	K^+	14 190
AMBER	^{12}C	100	K^+	$\simeq$140 000
	^{12}C	100	π^+	$\gtrsim$ 300 000

J/ψ production K/π ratio brings essential newl information

SUMMARY FOR J/ψ MEASUREMENTS WITH AMBER

- J/ψ data with π+ and π− beams (Run 3)
  - J/ψ and ψ' measurements with high statistics
  - Allow for multidimensional analysis of cross section and polarization data
  - Goal: understand production mechanism and infer meson PDFs
    - ✓ AMBER is unique for such measurements; no direct competition

- J/ψ data with K^-, K^+ and antiproton beams (Run 4 and RF separation)
  - J/ψ and ψ' data: extensive comparison K^- and K^+, possibly p and $\bar{p}$ data
  - Goal: constrain production mechanism + determine K valence and gluon structure
    - ✓ Motivating extensions with kaon and antiproton beams; no direct competition